1997

Identifying a collective variable of locomotion : a dynamic systems analysis

Jim Kao
San Jose State University

IDENTIFYING A COLLECTIVE VARIABLE OF LOCOMOTION:
A DYNAMIC SYSTEMS ANALYSIS

A Thesis

Presented to

The Faculty of the Department of Human Performance

San Jose State University

In Partial Fulfillment

Of the Requirements for the Degree

Master of Arts

by

Jim Kao

May, 1997

UMI Number: 1386765

APPROVED FOR THE DEPARTMENT OF HUMAN PERFORMANCE

V G Payne

Dr. V. Gregory Payne

Gail G. Evans

Dr. Gail G. Evans

E H W

Dr. Emily H. Wughalter

APPROVED FOR THE UNIVERSITY

Serena W. Stanford

ABSTRACT

A DYNAMIC SYSTEMS ANALYSIS OF LOCOMOTION:
IDENTIFYING A COLLECTIVE VARIABLE

By Jim Kao

A dynamic systems analysis was conducted to identify a collective variable of locomotion. Twenty subjects were between 20 and 29 years of age (mean = 25 years) and 20 subjects were between 30 and 39 years of age (mean = 33 years). Two collective variables (hip-ankle and knee-ankle relative phase angles) were evaluated. These evaluations were made as the value of a control parameter (horizontal velocity) was varied. Subjects performed four trials at increasing, self-selected speeds of walking and four trials at increasing, self-selected speeds of running. The trials were videotaped at 60 fields per second. Results of a two-dimensional analysis found that the attractor state (relative phase angle vs. % of stride) of each collective variable was qualitatively similar for the 4 walking trials. In addition, the attractor state for running was qualitatively similar among the 4 running trials, but qualitatively different from the attractor state for walking.

ACKNOWLEDGMENTS

I would like to thank the members of my thesis committee, Dr. Gail G. Evans and Dr. Emily H. Wughalter, for their guidance and assistance during the preparation of this thesis and for passing on their knowledge of biomechanics and motor learning, respectively.

I wish to express my deepest appreciation to my thesis committee chair, Dr. V. Gregory Payne, for his enthusiasm, inspiration, direction, and support during the preparation of this thesis and for the professional relationship and personal friendship we have developed during my two-and-one-half years at San Jose State University.

I would like to thank my parents, Timothy and Setsuko Kao, for their never-ending and unconditional love and support.

Finally, and most importantly, I would like to thank my wife, Darcy, for her love, encouragement, and assistance. I cannot adequately express in words the gratitude and love I have for her.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

In 1980, Kugler, Kelso, and Turvey (1980) theorized that the concepts of dynamic systems theory, previously developed in the fields of physics, biology, and chemistry, could be applied in the human movement behavior field of motor control. Following a series of experimental studies to test this theory, Kelso and Schöner (1988) developed seven theoretical propositions of coordinated human movement, within the context of dynamic systems theory, and an experimental strategy for their investigation. This strategy requires the identification of a collective variable which completely captures the essential characteristics of a movement pattern; the investigation of the collective variable's behavior (i.e., its attractor state) near a point of transition from one stable, movement pattern to a different stable, movement pattern; the identification of potential control parameters which drive the transition; and the investigation of the stability and loss of stability of the attractor state as the value of the control parameter is varied.

In this study, the movement behavior investigated was adult locomotion. Previous developmental research on gait patterns comparing normal, healthy younger and older adults have found that the values of kinematic walking parameters remain essentially constant between 20 and 60 years of age. After age 60, only minor changes in the values of kinematic walking parameters occur; the primary difference being that with increasing age, older adults walk more slowly (Craik, 1990). Thus, age as a control parameter yields no qualitatively different stable attractor states of walking. Therefore, another type of transition in locomotion behavior must be evaluated to assist in identifying a potential collective variable.

Walking and running are considered different fundamental locomotion patterns (Payne & Issacs, 1995). They are both characterized by an alternating pattern of interlimb coordination; the relative phase difference between the two legs is 180°. For both forms of locomotion, each leg alternates between a stance phase (i.e., foot in contact with the ground) and a swing phase (i.e., leg swinging freely). The qualitative difference between walking and running is the existence of two airborne, or float, phases (i.e., both feet are off the ground) and the lack of any double support phase (i.e., both feet in contact with the ground) during running (Òunpuu, 1994). Thus, walking and running are two qualitatively different states of locomotion. A possible control parameter that drives the transition from walking to running is the velocity of locomotion. At low velocities, either walking or running can be performed. But, as the velocity increases, a critical value will be reached where only running is possible. Hence, from a dynamic systems theory perspective, the study of the differences between walking and running as the velocity of locomotion increases is an appropriate experimental context for the identification of a collective variable of locomotion.

Previous research studies (Clark & Phillips, 1993; Clark, Truly, & Phillips, 1990; Clark, Whitall, & Phillips, 1988; Thelen, 1986; Thelen & Ulrich, 1991; Thelen, Ulrich, & Niles, 1987; Whitall & Getchell, 1995) have investigated changes in infant locomotion from a dynamic systems perspective. All of these studies selected subject age as the control parameter. The variables that may control the transition from walking to running were investigated in a series of studies performed by Hreljac (1993a, 1993b, 1995a, 1995b). Of the numerous linear and angular kinematic variables studied, Hreljac (1995a) concluded that only one, peak ankle angular velocity, is a possible determinant of the transition from walking to running as horizontal velocity is increased. Hreljac found that peak ankle angular velocity decreased significantly when subjects transitioned from fast walking to slow running. Thus, a collective variable of locomotion that takes into account peak ankle angular velocity appears to be appropriate for studying the similarities and differences in walking and running. Such a variable can be extrapolated from work conducted by Clark and Phillips (1993). Clark and Phillips used a collective variable that characterized locomotion as the coordination between the hip and knee. The variable quantified the relative phasing between motion at the hip and motion at the knee. This relative phasing took into account angular displacement and angular velocity at each joint. Combining the findings of Hreljac, and Clark and Phillips, leads to the identification of two potential collective variables of locomotion: relative phasing between the hip and ankle, and relative phasing between the knee and ankle.

Statement of the Problem

A collective variable of locomotion has yet to be identified which meets theoretical and adult developmental selection criteria. Two theoretical selection criteria were developed by Kelso and Schöner (1988). First, the collective variable must qualitatively distinguish between two different, stable attractor states of the same movement pattern (i.e., walking and running). Second, there must be an abrupt transition from one of the stable attractor states (i.e., walking) to the other stable attractor state (i.e., running) as the value of a potential control parameter (i.e., velocity of locomotion) is varied. After meeting the theoretical selection criteria, a collective variable of locomotion should then meet two adult developmental selection criteria. First, the attractor state for walking must be qualitatively similar for two different age groups of young adults. Second, the attractor state for running must be qualitatively similar for two different age groups of young adults.

Statement of Purpose

The primary purpose of this study was to test two collective variables of locomotion (hip-ankle relative phase angle and knee-ankle relative phase angle) against two hypotheses of dynamic systems theory: (1) the attractor state of the collective variable (relative phase angle plotted against percentage of stride cycle) during walking will remain qualitatively stable as the value of the control parameter (velocity of locomotion) is increased; and (2) the attractor state of the collective variable will qualitatively change to a different configuration during running and remain stable as the value of the control parameter is increased. A secondary purpose of this study was to qualitatively test whether the attractor state of the collective variable remains constant when the locomotion patterns of walking and running of two age groups of young adults are compared. A tertiary purpose of this study was to quantitatively test a prediction that the peak ankle angular velocity during slow running is significantly less than the peak ankle angular velocity during fast walking.

Hypotheses

This study experimentally tested six null hypotheses.

(1) No qualitative differences in the overall pattern of the attractor states of each collective variable will be evident when the four walking trials are compared.

(2) No qualitative differences in the overall pattern of the attractor states of each collective variable will be evident when the four running trials are compared.

(3) No qualitative differences in the overall pattern of the attractor states of each collective variable will be evident when the walking and running trials are compared.

(4) No qualitative differences in the overall pattern of the attractor states of each collective variable will be evident when the walking trials of the 20-29 year-old age group and the 30-39 year-old age group are compared.

(5) No qualitative differences in the overall pattern of the attractor states of each collective variable will be evident when the running trials of the 20-29 year-old age group and the 30-39 year-old age group are compared.

(6) Peak ankle angular velocity during the slow running trials will not be significantly different than peak ankle angular velocity during the fast walking trials.

Delimitations

This study used a cross-sectional design to experimentally examine qualitative and quantitative differences between walking and running in two age groups of adults: 20-29 years and 30-39 years. Each group consisted of 10 male and 10 female subjects. Each subject had no known neurological, pathological, or musculoskeletal conditions which affected walking or running. The speed of locomotion for each walking and running trial was self-selected by each subject. Two-dimensional analyses of gait were performed. For the dynamic systems analysis, two collective variables were analyzed: the relative phase angle between the hip and ankle, and the relative phase angle between the knee and ankle. The attractor state for each collective variable was relative phase angle plotted against percentage of the stride cycle. The control parameter was speed of locomotion. The dependent variable for the quantitative analysis was peak ankle angular velocity. The independent variables were age, gender, and type of locomotion trial.

Limitations

A cross-sectional design introduces the possibility that significant differences within each age group cannot be identified. Thus, a conclusion that no significant difference exists between the two age groups cannot be extrapolated to state that no significant change occurs between 20 and 29 years of age or between 30 and 39 years of age. The use of self-selected speeds of walking could result in walking or running trials performed at the same speed being included in different locomotion trial groups. Three-dimensional effects (out-of-plane movements), manual digitizing, anatomical markers obscured by other body parts, and anatomical markers attached to loose fitting shorts could introduce unexpected variability into the biomechanical analyses.

Definitions

attractor state: "Experimentally well-defined behavioral patterns (reproducible, stationary over certain observation times) correspond to stable collective states (or attractors) of the order parameter dynamics. Behavioral patterns can change only from one collective state to another" (Kelso & Schöner, 1988, p. 41).

collective variable:	"Behavioral patterns can be characterized by low dimensional collective variables . . . whose nature and dynamics are specific to biological functions and tasks" (Kelso & Schöner, 1988, p. 41).
control parameter:	"A parameter that moves the system through different collective states is a control parameter in the sense of synergetics" (Kelso & Schöner, 1988, p. 41).
coordinative structure:	"[A coordinative structure] is a group of muscles often spanning a number of joints that is constrained to act as a single functional unit" (Kugler et al., 1980, p. 17).
dissipative structure:	"An open system with nonlinearities that is maintained far from equilibrium is referred to as a dissipative structure" (Kugler et al., 1980, p. 15).
dynamic stability:	"Self-assembled behavior of complex systems is dynamically stable in any given context. Given a particular biological organization, and a particular context, we can say that the system prefers a certain range of behavioral outputs" (Thelen, 1989, p. 85).
limit cycle oscillator:	"Repetitive or cyclical behavior is characterized as a limit cycle oscillator" (Thelen, 1989, p. 85).
phase transition:	"Complex systems may exhibit multiple behavioral patterns. An important characteristic of such complex systems is that they switch between patterns in a discontinuous manner, by exhibiting discrete phase transitions" (Thelen, 1989, p. 87).
self-organization:	"Self-organization means that behavior emerges strictly as a cooperative function of the subsystems within particular environmental and task contexts" (Thelen & Ulrich, 1991, p. 24).

stochastic force: "Stochastic forces act as continuously applied perturbations therefore producing deviations away from the attractor state" (Kelso & Schöner, 1988, p. 36-37).

Operational Definition

healthy: An individual with no known, neurological, pathological, or musculoskeletal conditions which affect walking or running.

Need for the Study

In the next 60 years, the U.S. Department of Health and Human Services predicts the percentage of the population in the United States over the age of 65 years will increase from 12.6% to 22.9%, and the number of people over the age of 65 years will increase from 31.6 million to 68.7 million (U.S. Department of Health and Human Services, 1991). In 1986, a survey by the U.S. Bureau of the Census found that 9.3% of people between the ages of 65 and 69 years needed assistance with everyday activities, 18.9% of people between the ages of 75 and 79 years needed assistance with everyday activities, and 45.4% of people over the age of 85 years needed assistance with everyday activities (U.S. Bureau of the Census, 1990). The Centers for Disease Control and Prevention reported that in 1986, 18.2% of people over the age of 65 years, 25.8% of people over the age of 75 years, and 35.9% of people over the age of 85 years had difficulty walking (Centers for Disease Control and Prevention, 1993). In 1990, over 51% of people over the age of 65 years used walking for exercise (National Center for Health Statistics, Vital Health Statistics, 1993). Clearly, walking is an important daily activity which must be maintained at a functional level. It allows people to function in society and to maintain an appropriate level of physical fitness. Finding procedures for identifying individuals with dysfunctional walking patterns, individuals who are at risk for developing dysfunctional walking patterns, and possible treatment programs for delaying the onset or correction of dysfunctional walking patterns is important. Dynamic systems theory and the experimental strategy for examining coordinated movement behaviors may be important tools for identifying these procedures.

Summary

Dynamic systems theory offers an experimental strategy for studying coordinated human movement (Kelso & Schöner, 1987, 1988). The movement pattern of interest in this study is human locomotion. The key component of the dynamic systems experimental strategy is the identification of a collective variable that characterizes a coordinated movement pattern. Thus, the primary purpose of this study was to test two potential collective variables of locomotion against two theoretical requirements of the experimental strategy: (1) the attractor state of a collective variable will remain stable as the value of a control parameter is increased towards a critical value, and (2) after the value of the control parameter exceeds the critical value, a new, qualitatively different, attractor state of the collective variable will develop that remains stable with further increases in the value of the control parameter. The identification of a collective variable of locomotion could lead to the development of a testing procedure that may identify older adults with dysfunctional walking patterns. Such a procedure could aid in the evaluation of treatment programs for delaying the onset or correction of dysfunctional walking patterns.

CHAPTER TWO

REVIEW OF LITERATURE

In this chapter, a review of literature is presented related to the development and application of dynamic systems theory in the human movement behavior fields of motor control and motor development. In the first section, the key theoretical principles of dynamic systems theory are presented. It is followed by a summary of experiments that were conducted to test these principles on a coordinated human movement pattern. The results and findings of these experiments were used to develop seven theoretical propositions of coordinated human movement and a strategy for experimentally testing the seven propositions. A review of experimental studies that applied dynamic systems theory in the field of infant motor development is presented in the third section. The authors of these studies applied dynamic systems theory to the investigation of locomotion development in infants. The chapter concludes with a review of experimental studies that investigated the biomechanical determinants of the transition from walking to running.

Principles of Dynamic Systems Theory

In 1980, Kugler et al. (1980) presented a theoretical solution to the problem of coordinated human movement posited by Nicholas Bernstein in 1967 (Bernstein, 1967). They restated Bernstein's problem as follows: "How can the very many degrees of freedom of the body be regulated in the course of activity by a minimally intelligent executive intervening minimally?" (p. 4) In other words, how can a person use a minimal amount of cognitive control to coordinate the many degrees of freedom that exist in the musculoskeletal system (Kelso & Tuller, 1984). The theoretical solution presented by Kugler et al. (1980) has come to be known as dynamic systems theory.

Kugler et al. (1980) proposed that the degrees of freedom are dissipated systematically to reduce computational demands. They suggested that this dissipation occurs when the number of free variables to be regulated, the number of instructions per unit time, the number of decisions about the kind of instructions to be given, and the number of decisions about the timing of the instructions are kept at a minimum. Kugler et al. (1980) emphasized that constraints (both anatomical and functional) channel and guide the dynamics that account for ordered behavior in biological and physiological processes. They asserted that coordinated behavior is not caused by the constraints; rather, the constraints act to reduce the number of ways to perform the coordinated behavior.

Open, thermodynamic systems tend to exist in a steady-state that is displaced from entropic equilibrium. Entropic equilibrium is the final state of closed, isolated, thermodynamic systems. A system that reaches entropic equilibrium has maximum disorder, zero information, and cannot perform any work. The displacement of a system away from entropic equilibrium is accomplished by a periodic flow of energy into and out of the system. An open system displaced far from entropic equilibrium is known as a dissipative structure. It is generally characterized as stable and self-organizing. However, when the flow of energy into a stable, dissipative structure is increased beyond or decreased below a critical value, it gives way to instability. If the energy continues to increase or decrease, a new stable, dissipative structure will appear (Kugler et al., 1980).

Biological systems are a type of open, thermodynamic system. Energy flows into a biological system and actively organizes the system into a stable configuration. The cost of this stability is dissipation of the energy flowing into the system. The dissipated energy must be replaced on a periodic and continuous basis. The amount of supplied energy must equal the amount of dissipated energy. This creates a system that is dynamically stable (Kelso & Tuller, 1984).

Self-organization is the dramatic reduction in the number of degrees of freedom which can act independently when specific physical and thermodynamic conditions are placed on a system. It is a cooperative function of the body's subsystems, the environment, and the context of the task. None of these elements contains the instructions for performance of a movement behavior, and there is no hierarchy among the elements (Thelen & Ulrich, 1991).

If relationships can be identified which relate the degrees of freedom of one element to another, the total number of degrees of freedom required to define the system will be reduced. These relationships, known as equations of constraints, reduce the total number of degrees of freedom required to define the structure (Kugler et al., 1980). Equations of constraint can be thought of as dynamical linkages between the numerous degrees of freedom associated with human movement behavior. They reduce the amount of executive commands that are required to be issued by the cognitive process (Kelso & Tuller, 1984).

Two types of parameters are functionally a part of any equation of constraint: essential and nonessential. Essential parameters are determinants of the biological system's macroscopic (observable) qualities. Nonessential parameters have no impact on the macroscopic qualities of the system. The classification of parameters into either essential or nonessential is dependent on the energy state of the biological system. A change in energy level may cause an essential parameter to become nonessential and vice versa. The identification of essential and nonessential parameters allows the researcher to systematically modify the equations of constraint (Kugler et al., 1980).

Nonlinear differential equations are used to model dynamic systems. Differential equations can be solved quantitatively or qualitatively. Qualitative analyses are usually performed when trying to solve nonlinear differential equations. The result of a qualitative analysis is a phase portrait that represents the geometrical and structural characteristics of the range of solutions for the differential equation. A dissipative structure maintains the topological characteristics of its phase portrait (i.e., dynamic stability) even while its system parameters are varied. In other words, many variations in the system parameters of a dissipative structure can be qualitatively characterized by a few phase portraits (Kugler et al., 1980).

The dynamic stability of a dissipative structure can be represented by a closed cycle of events that is self-sustaining and non-linear (a limit cycle). Limit cycles are periodic attractors that are characterized by a relatively fixed, cyclical relationship between amplitude and frequency, a tendency to not resonate (increase in amplitude) at a preferred frequency, and a tendency to synchronize (mutually entrain) with other limit cycles. A limit cycle is a type of thermodynamic engine. Energy is dissipated during the orbital oscillation of the limit cycle. This dissipated energy is replaced by an equal amount of energy that is periodically supplied to the limit cycle. The supplied energy maintains the cyclical motion of the limit cycle (Kelso & Tuller, 1984; Kugler et al., 1980).

A graphical method is used to display the characteristics of a limit cycle. The displacement, at time t, of an essential parameter of the limit cycle is plotted against its velocity, at the same time t. A limit cycle plotted in such a manner will display a closed, cyclical trajectory. This closed, cyclical trajectory is an indicator of the limit cycle's dynamic structural stability. When a limit cycle is perturbed, it will quickly return to the stable trajectory. When two or more limit cycles interact, they will do so in a cooperative and self-organizing manner (Kelso, Holt, Rubin, & Kugler, 1981).

Dissipative structures exhibit a limited number of dynamically, stable configurations. When the energy flow into a dissipative structure is increased above or decreased below a critical value, a discontinuous phase transition can occur. In other words, the system can abruptly change from one dynamically, stable configuration to another dynamically, stable configuration. The phase transition is representative of an unstable configuration for the dissipative structure. An unstable dissipative structure will either return to the original stable configuration, or it will find a new stable configuration. Discontinuous phase transitions are an essential feature of nonlinear, dynamic (Kelso & Tuller, 1984; Kugler et al., 1980).

Bernstein's problem, how can the brain exert minimal effort when it controls the many degrees of freedom associated with human movement, can be solved by a systematic linkage of the numerous muscles in the human body into smaller muscle collectives called coordinative structures. Coordinative structures are groups of muscles spanning a number of joints that are constrained to act as a single unit. The grouping does not represent a state of entropic equilibrium. Instead, the linkage between the different muscles represents a state far from entropic equilibrium that is maintained by periodic input of energy from internal or external sources; In other words, a coordinative structure is a type of dissipative structure. Therefore, the characteristics of a coordinative structure will be the same as the characteristics of a dissipative structure; it will exhibit self-organization, dynamic stability, and phase transitions (Kelso, Holt, Kugler, & Turvey, 1980; Kugler, Kelso, & Turvey, 1980, 1982).

Understanding Coordinated Biological Movement

Between 1980 and 1987, a series of experimental research studies and mathematical modeling efforts were performed to verify the applicability of dynamic systems theory to coordinated human movement. The studies and mathematical modeling efforts were focused on the simultaneous oscillations of the wrists or the fingers. These studies investigated the three major predictions of dynamic systems theory: the movements are self-organizing, the movements will demonstrate dynamic stability (specifically, the movements can be modeled as a system of coupled, limit cycle oscillators), and the movements will go through a phase transition when a control parameter is linearly increased past a critical value. Each of these will be discussed in the following sections.

Self-Organization

In 1980, Yamanishi, Kawato, and Suzuki (1980) presented the results of their study on coordinated finger tapping. The authors hypothesized that the coordinated tapping of one finger on each hand is controlled by the interaction of two independent neural networks. Subjects in the study were trained to produce 10 different tapping patterns. Each pattern represented a different phasing relationship between the two fingers. A 0.0 tapping relationship represented a synchronous (in-phase) relationship between the fingers. A 0.5 tapping relationship represented an asynchronous (anti-phase) relationship between the fingers. The remaining eight phasing relationships were 0.1, 0.2, 0.3, 0.4, 0.6, 0.7, 0.8, and 0.9.

During training, the subjects received continuous pacing signals for the different phasing relationships. During testing, only 10 pacing signals were given in the beginning. Subjects were then instructed to continue tapping the required phasing relationship until ordered to stop. The authors measured the accuracy of the phasing relationship during the self-paced portion of each test trial. Two groups of subjects were tested: a novice group (normal motor functions) and a skilled group (pianists).

Yamanishi et al. found both groups maintained the 0.0 and 0.5 phasing relationships more accurately. They found that errors made for phasing relationships near 0.0 (e.g., 0.1, 0.2, 0.8, and 0.9) tended to resemble the 0.0 phasing relationship. Additionally, the errors made for phasing relationships near 0.5 (e.g., 0.3, 0.4, 0.6, and 0.7) tended to resemble the 0.5 phasing relationship. The authors concluded that only two stable relationships exist for coordinated finger tapping: synchronous (in-phase) and asynchronous (anti-phase).

In 1982, Baldissera, Cavallari, and Civaschi (1982) reported the findings of their study on ipsilateral coordination of wrist and ankle movements. The authors performed two experiments. In the first experiment, subjects performed wrist flexion and extension while the arm was pronated. In the second experiment, the subjects performed wrist flexion and extension while the arm was supinated. For both experiments, the ankle alternated between dorsiflexion and plantar flexion. The synchronous (in-phase) relationship was defined as movement at both joints in the same direction. The asynchronous (anti-phase) relationship was defined as movement at both joints in opposing directions.

Baldissera et al. found only two stable modes existed at low frequencies of oscillation (synchronous and asynchronous). At high frequencies of oscillation, only the synchronous oscillation mode was found. Increased oscillation frequency in the synchronous mode did not cause a phase transition to the asynchronous mode. However, for trials which started with low frequency oscillation in the asynchronous mode, an increase in frequency caused a dramatic switch to the synchronous mode.

In studies performed during the early 1980s, Kelso (1981, 1984) reported findings on the self-organizational characteristics of coordinated oscillatory movements of the wrists and of the fingers. In his experiments, Kelso's subjects oscillated either their wrists or their fingers in an asynchronous mode. The frequency of oscillation was gradually increased. The interlimb phase relationship was measured.

Kelso (1981, 1984) found that as the frequency of oscillation was increased, there was an abrupt phase shift from the asynchronous mode to the synchronous mode of oscillation. He found that over a range of frequencies below the transition frequency the asynchronous mode was stable. And he found that above the transition frequency the synchronous mode was stable. Kelso concluded that only two stable modes exist. He stated that other modes of oscillation do exist, but they are less stable. Kelso also concluded that oscillation frequency is a control parameter for this coordinated movement because it drives the phase transition from one stable state (asynchronous) to another stable state (synchronous). Kelso also suggested that the underlying cause of this phase transition, a parameter that cannot be experimentally measured, is the body's tendency to use more energetically efficient modes of coordination.

In 1985, Haken, Kelso, and Bunz (1985) developed a mathematical model of phase transitions for the coordinated oscillation of human fingers. They selected the relative phase of oscillation between the fingers as their collective variable. The collective variable is a low-dimensional variable which completely characterizes the movement pattern of a high-dimensional system. It systematically dissipates the high number of degrees of freedom in a system into a system with one or a few degrees of freedom. Even though the collective variable is a low-dimensional variable, it can have very complex movement characteristics.

This model is based on nonlinear oscillator theory. Each finger is modeled as an individual limit cycle oscillator. The model couples these individual oscillators into a nonlinear system. As suggested by Kelso (1984), the model uses the frequency of oscillation as the parameter which controls the phase transition (the control parameter) from the asynchronous mode to the synchronous mode of oscillation. The model successfully recreated the experimental results presented by Kelso (1984). The authors concluded that the individual movement and the coordinated movement of the oscillating fingers are nonlinear phenomena, and that coupled nonlinear oscillators insure "stability and flexibility of motor function." (Haken et al., 1985, p. 355)

Dynamic Stability (Limit Cycle Oscillators)

In 1981, Kelso et al. (1981) performed a series of experiments to test the dynamic stability of coordinated finger oscillations. The subjects performed cyclical oscillations of the index finger on each hand. The fingers oscillated together in an in-phase pattern. The authors measured the system's response to a perturbation of one finger. The dependent variables were relative phase, oscillation amplitude, and oscillation frequency. The authors studied the effect of the perturbation on individual finger oscillation frequency, the relative phasing relationship between the fingers, mutual entrainment of the fingers, and subharmonic entrainment of the fingers.

Kelso et al. (1981) found that individual finger oscillating frequency was dynamically stable (i.e., remained constant) before and after perturbation. They also found that the fingers were mutually entrained (i.e., their phasing relationship remained at a constant one-to-one ratio) before and after the perturbation. When the fingers were oscillated at slightly different frequencies, they were found to be attracted to a mutual frequency which was between the different frequencies (i.e., mutual entrainment). A stable phasing relationship between the fingers only occurred when the frequencies of oscillation were linearly related (i.e., 1:1, 2:1, 3:1). This is an example of subharmonic entrainment. The authors concluded that human limb coordination is accurately modeled by a system of nonlinear limit cycle oscillators.

Phase Transitions

In 1985, Kelso and Scholz (1985) conducted experiments to test the phase transition prediction of dynamic systems theory when the index fingers of each hand are oscillated in symmetrical and antisymmetrical phasing relationships. They hypothesized that the collective variable would demonstrate enhanced fluctuations and critical slowing as the transition from the antisymmetrical phasing relationship to the symmetrical phasing relationship was approached.

Kelso and Scholz (1985) found that as the frequency of oscillation was increased the antisymmetrical phasing relationship of the fingers switched to a symmetrical phasing relationship. As the frequency of oscillation approached the transition frequency, the system took more time to return to the asymmetrical phasing relationship when a small deviation in the relationship was imposed. The authors concluded that this result was experimental evidence of critical slowing. In addition to providing evidence of critical slowing, the experiment also provided evidence of enhanced fluctuations. As the frequency of oscillation approached the transition frequency, the variance of the collective variable increased.

In 1986, Schöner, Haken, and Kelso (1986) developed a mathematical model for the phase transition phenomenon found in previous experiments (Kelso, 1981, 1984; Kelso &

Scholz, 1985). This model was built on the model previously developed by Haken et al. (1985). It added stochastic forces to the nonlinear, dynamic systems model. These stochastic forces were included to address the experimental findings of Kelso and Scholz (1985). To incorporate these findings, Schöner et al. defined three important time scales. Relaxation time (τ_{rel}) is the time it takes a system displaced from a stable configuration to return to the stable configuration. Parameter change time (τ_p) is the time between experimental changes in the control parameter. Equilibration time (τ_{eq}) is the time necessary for a system to change from one stable configuration to another stable configuration. Stochastic theory predicts that a system far from a transition will have the following relationship $\tau_{rel} << \tau_p << \tau_{eq}$, and that a system at transition will have this relationship $\tau_{rel} \approx \tau_p \approx \tau_{eq}$.

Schöner et al.'s (1986) model made three theoretical predictions. First, τ_{rel} is constant when the system is far from transition. As the system gets closer to transition, τ_{rel} will get closer to τ_p. The increase in τ_{rel} is defined as critical slowing. Second, the collective variable will experience increased fluctuations during transition. Third, during transition, τ_{eq} will approach τ_p. The switching time occurs when τ_{eq} becomes less than τ_p. This model successfully duplicated the experimental results of Kelso & Scholz (1985).

Kelso, Schöner, and Scholz performed two experiments to test the theoretical predictions of the stochastic model (Kelso, Scholz, & Schöner 1986; Scholz, Kelso, & Schöner, 1987). Kelso et al. (1986) tested the theoretical prediction of critical fluctuations. In this study, subjects performed rhythmic oscillations of the fingers or wrists. The oscillations began in either the in-phase mode or anti-phase mode. The frequency of oscillation was increased and the relative phase between the fingers was measured. The authors found that an abrupt transition only occurred from the anti-phase mode to the in-phase mode. As the frequency of oscillation approached the transition frequency, the fluctuations in the relative phasing of the fingers increased and the fluctuations were at a maximum during the transition. The authors concluded that the results of this experiment verified the theoretical prediction of a stochastic model for coordinated biological movement.

In 1987, Scholz et al. (1987) performed a second experiment to test the stochastic model. In this experiment, the authors tested the predictions of critical slowing and switching time. The experimental setup was similar to the one used by Kelso et al. (1986). For this experiment, relaxation time (τ_{rel}) was measured. One finger was perturbed, and the time required to restabilize the oscillation pattern was recorded. This was then compared to the parameter change time (τ_p) = 10 seconds. Equilibration time (τ_{eq}) was estimated as the mean first passage time (MFPT). MFPT is the time of transition from the anti-phase mode to the in-phase mode. It can be calculated at different oscillation frequencies based on characteristics of the system. Scholz et al. found that τ_{rel} increased in the anti-phase mode. It remained constant in the in-phase mode as the frequency of oscillations approached the transition frequency. This provided clear evidence of critical slowing in the anti-phase mode of oscillation. The authors also found the τ_{eq} (prior to transition) was 13.0 seconds, and the τ_{eq} (at transition) was 5.35 seconds. This experimental evidence confirmed the theoretical prediction that switching time occurs when τ_{eq} becomes less than τ_p.

Theoretical Propositions

From the results from the empirical research and mathematical modeling, Kelso and Schöner developed seven theoretical propositions for behavioral stability and change (Kelso & Schöner, 1987; Schöner & Kelso, 1988).

(1) A collective variable is a low-dimensional variable which completely captures the characteristics of a specific movement pattern of a high-dimensional biological organism.

(2) Stable collective states or attractors of the collective variable are well defined patterns that remain constant during a period of observation.

(3) A control parameter can be the environmental content, task variables, or structural condition that drives a system from one attractor to another attractor.

(4) Time scale relationships (τ_{rel}, τ_p, & τ_{eq}) are evaluated to determine if a system is losing stability or if fluctuations in a system are merely background noise.

(5) Behavioral change or phase transitions occur when a system loses stability.

(6) Behavior patterns at any level (neuron, muscular, or kinematic) can be modeled by collective variables and the propositions of dynamic systems theory are applicable.

(7) A coupling of nonlinear limit cycle oscillators can model a number of specific biological collective states.

The Experimental Strategy

To test the theoretical propositions of behavioral pattern stability and change, Kelso, Schöner, Scholz, and Haken developed an experimental strategy or operational approach to investigating coordinated biological movement (Kelso & Schöner, 1988; Kelso, Schöner, Scholz, & Haken, 1987). This strategy provides a link between experiment and theory. Its main components are:

(1) identify a collective variable.

(2) define stable attractor states of the collective variable.

(3) determine control parameters that push the system through its different attractor states.

(4) study the phase transition between stable attractor states to determine system dynamics.

(5) determine relationships between different levels of observation (neuronal, muscular, and kinematic) by investigating collective variable dynamics that result from the cooperative coupling among these components.

Dynamic Systems Theory and Motor Development

Treadmill Stepping

In a series of experiments in the late 1980s and early 1990s, Esther Thelen and her associates (Thelen, 1986; Thelen & Ulrich, 1991; Thelen et al., 1987) investigated the self-organizing nature of human locomotion from a motor developmental perspective. Thelen (1986) conducted a study which demonstrated that well before an infant can walk independently, the mature stepping pattern already exists. Six, 7-month-old infants were recruited and tested for the study. The walking pattern of one adult was videotaped and used for comparison with the infants. Each infant was supported under arms and then lowered, in a vertical position, onto a moving treadmill. The treadmill was operated at 2 speeds: slow (.10 m/s) and fast (.19 m/s). The movements of the infants' legs while on the treadmill were videotaped. Hip, knee, and ankle joint movements for 3 consecutive steps were digitized. Calculations were performed to determine joint angles. The results of the study demonstrated that: the infants were able to immediately perform an alternating step pattern; they were able to coordinate the angular movements of the hip and knee; and they increased their stepping rate in response to increases in the treadmill speed. Thelen concluded that the dynamic constraints provided by the treadmill brought forth a complex movement pattern that no infant could perform on his or her own. This is an indication that walking is a self-organizing and emergent movement behavior.

Thelen et al. (1987) followed the study performed by Thelen (1986) with a study that investigated the responsiveness of the emergent walking pattern to perturbations introduced into the system. The authors hypothesized that the infants would automatically adjust their method of walking to maintain an alternating step pattern. Eight, 7-month-old infants were recruited for this follow-up study. To perturb the system a split-belt treadmill was utilized during the walking trials. Each belt was independently controlled and could be operated at a variety of speeds. Each infant was tested under four conditions: slow/slow, fast/fast, R slow/L fast, and R fast/L slow. The slow speed was .10 m/s and the fast speed was .20 m/s. The dependent measure was the phase lag between the legs. The study confirmed the findings of Thelen (1986) for both the slow/slow and fast/fast conditions. For both the R slow/L fast and R fast/L slow conditions, the infants made immediate adjustments to maintain an alternating step pattern. Thelen, Ulrich, and Niles concluded that: the alternating step pattern demonstrated by the subjects was highly coordinated and entirely spontaneous; interlimb coordination was maintained under varying conditions by the body's response to a changing environment; the central nervous system responds to these changes and an appropriate walking pattern emerges; and the movement control system corrects itself.

In 1991, Thelen and Ulrich (1991) performed another test with the split-belt treadmill. In this experiment, nine infants were tested twice a month for the first seven months of their lives. The two monthly tests took place within 2-3 days of each other. Ten conditions were tested: eight trials with both belts simultaneously increasing in speed from .11 m/s to .29 m/s; one trial with the right treadmill belt operating at .11 m/s and the left treadmill belt operating at .23 m/s; and one trial with the right treadmill belt operating at .23 m/s and the left treadmill belt operating at .11 m/s. Relative phase lag between legs was measured and compared to an expected phase lag of 0.5 (the phase lag for a mature walker). By four months, the infants were approaching the 0.5 phase lag, and by six months, the infants had stabilized near the 0.5 phase lag. As the infants grew older, they made rapid adjustments to changes in treadmill speeds, and they were able to maintain a phase lag near 0.5 under both split belt conditions. The authors concluded that locomotion is a property that emerges during infant development.

Independent Walking (The First Year)

In another series of experiments, Jane Clark and her associates (Clark & Phillips, 1993; Clark et al., 1990; Clark et al., 1988) experimentally investigated the dynamic stability of infant walkers during the first year of independent walking. The purpose of the Clark et al.'s (1988) study was to determine the characteristics that define interlimb coordination in the newly walking infant. They studied infants during the first six months of independent walking. They also studied newly walking infants under a supported walking condition. The authors were trying to find a coordinative structure for the interlimb coordination of walking. New walkers were defined as infants who were capable of performing at least three and no more than four independent walking steps. This study used a cross-sectional design. Six groups of infants were recruited for the study. Five infants were included in each of the following groups: new walkers (supported), new walkers (unsupported), 0.5 months walkers, 1.0 month walkers, 3.0 month walkers, and 6.0 month walkers. A comparison group of five adult walkers was also tested.

All walking trials took place on a 10' x 2' walkway within the biomechanics lab at the University of Maryland. A Photosonics 16mm camera was located 23-24 feet away from the walkway, and the optical axis of the lens was perpendicular to the direction each subject walked. For the infant walking trials, a 25mm lens was used. This allowed filming of 6-7 step cycles. For the adult walking trials, a 16mm lens was used. This allowed filming of 3-4 step cycles. New, 0.5, and 1.0 month walkers were filmed at 32 frames per second (fps). The 3.0 and 6.0 month walkers were filmed at 50 fps. And, the adult walkers were filmed at 64 fps. The film data were digitized using a Numonics 1224 digitizer. Two types of interlimb phasing were calculated: temporal (the percentage of a walking cycle that has been completed when the opposite leg begins its step) and distance (the percentage of the total stride length covered when the opposite leg begins its step). The means and standard deviations for each variable were compared between the groups. A MANOVA was performed with a follow-up univariate analysis and a Newman-Keuls post hoc analysis (Clark et al., 1988).

The MANOVA indicated that significant differences existed between groups. There were no significant differences in temporal phasing. For variability of temporal phasing, the unsupported new walkers were significantly different from all other groups except the 0.5 month walkers. With increasing age, the number of significant differences decreased. By three months, there were no significant differences. There was only one group that had significantly different results for distance phasing; the supported walkers were significantly different from all other groups. For the variability of distance phasing, there were no significant differences between the new (unsupported), the 0.5 month, and the 1.0 month walkers. These walkers demonstrated variabilities that were significantly different from the other groups. There were no significant differences between the 3.0 month, 6.0 month, and adult walkers. New, supported walkers had significant differences only with the adults. Clark et al. (1988) concluded that the interlimb coordinative structure of infant walkers is very similar to adults. The structure is loosely coupled (i.e., more variable) during the first three months of walking, but the coupling gets progressively tighter after three months of walking. Intralimb coupling may impart constraints on the system that caused the different results for temporal and distance phasing. Postural support may be a possible control parameter.

Clark et al. (1990) reported on their attempts to identify a collective variable of locomotion. For intralimb coordination (i.e., coordination between the thigh and shank), the authors suggested that the relative phase angle between the thigh and shank is a possible collective variable appearing to measure the amount of intralimb coordination. The authors recommended that any phasing relationship should be examined at critical points in the gait cycle and also continuously throughout the gait cycle.

In 1993, Clark and Phillips (1993) conducted a dynamic systems analysis of the emergence of intralimb coordination during the first year of independent walking. They sought to identify a collective variable for the intralimb coordination and to examine potential control parameters that might drive the development. This was a one-year longitudinal study of three infants. Three adults were also tested for comparison purposes.

The infants were filmed weekly during the first month and monthly thereafter. Independent walking was defined as the ability to perform three independent steps. Joint markers were placed on the hip, elbow, shoulder, knee, ankle, and toe. The infant walking trials were conducted on a 3.0 x 0.6 meter walkway within the biomechanics lab at the University of Maryland. A Photosonics 16mm camera with a 25mm lens was located 7 meters away from the walkway. The optical axis of the lens was perpendicular to the path of walking. This arrangement allowed filming of at least four complete walking cycles. The adults were filmed outdoors at a running track. The Photosonics 16mm camera was located 20 meters away from the track. The camera was fitted with a 16mm lens. This allowed filming of at least four walking cycles for the adults. The filming rate for the infant walkers was 50hz and 100hz for the adult walkers (Clark & Phillips, 1993).

Data collected at the onset of walking, at weeks 2 and 4, and at months 2, 3, 6, 7, 9, and 12 were digitized. A walking cycle was defined as occurring between toe-offs of the same foot. A Butterworth, low pass filter with a 6hz cutoff was used to smooth the data. Standard kinematic analysis programs were used to calculate segment kinematic parameters. Phase portraits of the relationship between angular velocity and angular displacement were created for the shank and for the thigh. Angular velocity and angular displacement data at each point in the walking cycle were also converted into a phase angle relationship. The phase angles of the shank and thigh were used to calculate the relative phase angle between the segments. This relative phase angle was then plotted throughout the walking cycle. Several traditional gait parameters were also determined: stride length, velocity, stride frequency, percent of cycle in double support, and relative stride velocity (velocity divided by leg length). These parameters were investigated to identify potential control parameters. (Clark & Phillips, 1993)

The data analysis yielded the following results. Individual segment phase portraits displayed characteristics indicative of limit cycle attractors. Initially, the phase portraits of the infants and the adults were very different; but by 12 months, the patterns were very similar. The adult subjects displayed a very stable pattern for the relative phasing of the segments during the walking cycle. The pattern was nonlinear as predicted by dynamic systems theory. By three months, the infant walkers had relative phase diagrams that resembled the adult walkers; and by 12 months, the infant walkers had relative phase diagrams that were similar, but not equal, to the adult walkers. Clark and Phillips (1993) concluded that the individual limit cycle attractors and the coupled limit cycle system of the younger infant walker are very unstable. However, over the course of one year, the individual attractors and the coupled system move towards stable, adult-like patterns. The results of this study confirmed that relative phasing of the shank and thigh meets the theoretical predictions of dynamic systems theory for a collective variable. The relative phasing demonstrated a period of instability that over time stabilized in a mature walking pattern. The authors suggested that muscular strength and balance are possible control parameters that move the collective variable through the period of instability and into a stable attractor state. The authors concluded by stating that further research related to the development of locomotion is needed.

The Transition from Walking to Running

During their review of literature, Whitall and Getchell (1995) found that considerable motor development literature focused on the development of upright locomotion in infants, but very few studies examined infant running. Thus, Whitall and Getchell conducted a study which compared walking and running of four infants (three male and one female) and four adults (three male and one female). A dynamic systems analysis was performed. Seven potential collective variables (relative stance time, path of the center of mass, lowest negative position (LNP) of the shank, ratio of the positive to negative (PNV) shank velocities, coupling of the ankle and knee, ankle phase portrait (angular displacement versus angular velocity), and knee phase portrait) were descriptively examined during the study.

Each subject was videotaped by a NAC high-speed video camera operating at 60 Hz as they walked and ran along an indoor walkway. The infants were videotaped at 5.5, 7.5, and 9.5 months after beginning to walk independently (5.5 IW, 7.5 IW, and 9.5 IW), and then again at 3 years of age. An ExpertVision Motion Analysis System was used to digitize and smooth the raw data. A computer analysis program developed by G. E. Caldwell was used to analyze the conditioned data. Stride time, stride length, stride velocity, absolute stance time, and relative stance time were determined. Wilcoxin Matched Pairs Tests, a nonparametric statistical test, were used to statistically analyze each variable at an alpha of 0.01. Time lag analyses were performed to determine the relationships between flexion and extension of the ankle and knee. Angular velocity versus angular acceleration phase portraits were prepared for the ankle and the knee at each age and for walking and running (Whitall & Getchell, 1995).

Whitall and Getchell (1995) found for walking and running, velocities were significantly different for each age group. For the 5.5 IW and the 7.5 IW groups, changes in velocity were accompanied with significant changes in stride time, but not stride length. For the 9.5 IW, 3 year, and adult groups, changes in velocity were accompanied with significant changes in stride time and stride length. Relative stance times during running for the infants at each age of analysis were greater than 45%. The adults maintained a 43.6% relative stance time during their running trials. Whitall and Getchell found in previous studies that a relative stance time less than 50% was accepted as the transition from walking to running. However, during this study, they found that all of the infant runners exhibited at least one relative stance time which exceeded 50% and one adult exhibited a relative stance time which exceeded 50%. Movement of the center of mass at 5.5 IW, 7.5 IW, and 9.5 IW was similar for the walk and run. At 3.0 years the movement of the center of mass for the walk and run were obviously different and were beginning to resemble the movements of the adults. The authors found no significant differences for LNP or PNV between the infants at 5.5 IW and 7.5 IW. Significant differences were first apparent between 7.5 IW and 9.5 IW. The results of a cross-correlation analysis found a negative correlation between the flexion/extension of the ankle and the knee. The relative lag between similar points in each joint's range of motion was consistent for each type of gait and there were significant differences between the two types of gait. Qualitative review of the joint phase portraits revealed stable joint action for both types of gait at each age. A review of relative stability indicated a more stable phase portrait for the knee when compared to the ankle.

In general, Whitall and Getchell (1995) found that the collective variables being evaluated demonstrated continuous variation rather than abrupt transitions from walking to running. The one collective variable which did not change continuously was intralimb coordination as evaluated by phase lag of ankle motion relative to the knee motion. The authors suggested that the ability to generate and regulate forces that cause plantar flexion may be a control parameter for the phase transition from walking to running. The authors drew one general conclusion based on the results of the study: walking and running are two different, stable attractor states of human locomotion.

Determinants of the Transition from Walking to Running

In a series of experiments, Alan Hreljac studied physiological and biomechanical factors that may be determinants of the transition from walking to running. In the first experiment (Hreljac, 1993b), he tested two hypotheses: that the speed of locomotion at the transition from walking to running was driven by the body's effort to minimize metabolic energy (VO_2); and that the Rating of Perceived Exertion (RPE) while walking at the preferred transition speed (PTS) was equal to the RPE while running at the PTS.

Ten male and ten female subjects, all active and physically fit, participated in the study. Each subject performed walking and running trials on a motorized treadmill. During the walking trials, VO_2 data were collected while each subject walked at 70%, 80%, 90%, 100%, and 110% of their PTS. During the running trials, VO_2 data were collected while each subject ran at 90%, 100%, 110%, 120%, and 130% of the PTS. The PTS for each subject was determined on the day preceding the walking and running trials. A standing VO_2 value was obtained for each subject immediately before each subject began his or her experimental trials. All VO_2 data collected during the trials were normalized for each subject's standing VO_2, body mass, and actual speed of locomotion. This yielded a cost of transport VO_2 with units of $ml \cdot kg^{-1} \cdot km^{-1}$. RPE scores were collected for only two trials: walking and running at 100% of the PTS. Walking and running cost of transport VO_2 data were plotted versus speed of locomotion. A least squares regression analysis was performed to develop equations which fit each set of data. These equations were plotted together and velocity at the intersection of the two curves was chosen to be the energetically optimal transition speed (EOTS). Paired t-tests were performed to compare the EOTS and the PTS, the VO_2 values while walking and running at the PTS, and the RPE scores while walking and running at the PTS. An effect size, ES, was calculated for each comparison (Hreljac, 1993b).

Hreljac (1993b) found that the PTS was significantly lower than the EOTS, the VO_2 while walking at the PTS was significantly lower than the VO_2 while running at the PTS, and the RPE walking at the PTS was significantly greater than the RPE while running at the PTS. The ES for each comparison was determined to be large (ES>0.8). Hreljac concluded by stating that the results of this study contradict the assumption of other researchers that the human gait transition from walking to running is an energy saving mechanism. He suggested that an individual's RPE may reach a critical value at the gait transition and that a mechanism related to RPE may be the factor that determines the PTS.

After completing the first experiment, Hreljac tested the hypothesis that kinetic factors drive the walk to run transition in human beings (Hreljac, 1993a). Ten healthy male and ten healthy female subjects with a mean age of 23.9 years participated in the study. Hreljac established three criteria for identifying a kinetic variable that is a determinant of the transition from walking to running: (1) it must increase in value for each of three different loading conditions; (2) it must demonstrate an abrupt drop in value when running at the preferred transition speed (PTS) when compared to walking at the PTS; and (3) the value of the kinetic variable at the PTS for each of three different loading conditions must be the same. After reviewing the research literature on the kinetics of walking and running, Hreljac selected four variables for evaluation during the study which met the first two evaluation criteria: maximum braking force (FB_{max}), maximum propulsive force (FP_{max}), braking impulse (BI), and propulsive impulse (PI). In addition, Hreljac selected a fifth variable, resultant ground reaction force (GRF), for evaluation even though the literature did not indicate that resultant GRF met the first two evaluation criteria.

Each subject performed three sets of five locomotion trials: four walking trials (one each at 70%, 80%, 90%, and 100% of the subject's PTS) and one running trial (at 100% of the subject's PTS). Each set of locomotion trials was performed under a different additional load condition: no additional weight, an additional 10% of body weight, and an additional 20% of body weight. For each of the 15 walking trials, the subject was asked to walk or run down a runway and over a force platform. All force data collected from the force platform were normalized to subject body weight. A repeated measures MANOVA was used to compare the five kinetic variables under the three different loading and five different speed conditions (Hreljac, 1993a).

The mean value of FB_{max} for the 20% loaded condition was significantly greater than the mean value of FBmax for the 10% loaded and the unload conditions. The mean value of FP_{max} for the 20% and the 10% loaded conditions were both significantly greater than FP_{max} for the unloaded condition. Therefore, FB_{max} and FP_{max} did not satisfy the third evaluation criteria and were eliminated as possible determinants of the walk to run transition. The mean values for BI and PI did not significantly change under any loading condition as the speed of walking was increased. Therefore, BI and PI did not satisfy the first evaluation criteria and were eliminated as possible determinants of the walk to run transition. Finally, the mean values for resultant GRF under all three loading conditions significantly increased after the transition from walking to running. Therefore, the resultant GRF did not meet the second evaluation criteria and was eliminated as a possible determinant of the walk to run transition. Hreljac concluded that kinetic factors were not determinants of the transition from walking to running (Hreljac, 1993a).

In 1995, Hreljac conducted his third and fourth studies on the transition from walking to running during human locomotion. In the third study (Hreljac, 1995a), he hypothesized that a kinematic factor could be the determinant of the transition from walking to running. He presented four evaluation criteria for identifying a kinematic variable that was a determinant of the transition: (1) the variable must abruptly change after the transition; (2) the value of the variable must return to a value that was identified at a lower speed of walking; (3) the variable must be able to elicit a response by proprioceptors such as muscle spindles or joint receptors; and (4) the value of the variable must be the same at the transition under three different conditions of treadmill incline. A literature review of previous research was conducted and only four kinematic variables were identified that met the first three evaluation criteria: maximum hip extension angle, support length, peak ankle angular velocity, and peak ankle angular acceleration. This study directly tested whether any or all of these kinematic variables would meet the fourth evaluation criteria.

Ten healthy male and ten healthy female subjects with a mean age of 24.1 years participated in the study. Each subject performed four walking trials (one each at 70%, 80%, 90%, and 100% of the subject's PTS) and one running trial (at 100% of the subject's PTS) under three different treadmill incline conditions. The subjects performed a separate walking trial for each speed condition. In other words, the transition from 70% to 80% and so on was not continuous. All subjects were videotaped in the sagittal plane by a Panasonic AG-450 video camera operating at 60 Hz. Raw data were digitized and then smoothed using a fourth order zero-lag Butterworth filter. To account for variations in subject posture and for variations in marker placement, changes in kinematic data were calculated relative to each subject's individual static, standing posture. Videotaping of the static, standing posture of each subject on the treadmill was performed immediately prior to the beginning of the walking and running trials. A repeated measures MANOVA was used to compare the five kinematic variables under the three different incline conditions and five different speed conditions (Hreljac, 1995a).

Evaluation criteria one and two were met by all four investigated kinematic variables. Hreljac did not directly test the third evaluation criteria but stated that "this criterion was speculated to be met by all of the dependent variables" (p. 672). Peak ankle angular velocity was the only dependent variable to meet the fourth evaluation criteria. Hreljac concluded that peak ankle angular velocity was the only kinematic variable that determines the transition from walking to running. Hreljac hypothesized that the transition from walking to running was driven by the body's protection of the small dorsiflexor muscles and that at the PTS these muscles may be working near their maximum capacity (Hreljac, 1995a).

In the fourth experiment, Hreljac investigated the effects of anthropometrics on the PTS from walking to running (Hreljac, 1995b). He hypothesized that anthropometric length variables and body composition will be significantly correlated with the value of the PTS. He did not specify a correlation direction (positively or negatively correlated) in his hypothesis. Thirteen healthy male and 15 healthy female subjects with an average age of 24.0 years participated in the study. Six dependent variables were evaluated: % body fat (BF), lateral malleolus height (LM), tibial height (TiH), trochanteric height (TrH), thigh length (TL), and sitting height (SH). Correlation coefficients were determined by one-tailed tests of significance ($\underline{p} < .05$).

Hreljac found that anthropometric length variables were more highly correlated to PTS in males. He attributed this finding to slightly greater variability in PTS and in the length variables for the males. In general, he found the correlation between all length variables and the PTS to be weak for the entire group. When two outliers were removed from the analysis, the correlation was moderate. No single length variable was more highly correlated to PTS than any other length variable. A multiple regression equation was developed that explained 57% of the variance in the PTS. Lateral malleolus height was the variable that contributed the most in this equation. Hreljac concluded that even though there is a correlation between anthropometric measures and the PTS, it is weak to moderate at best (Hreljac, 1995b).

Summary

The development of dynamic systems theory in the field of human movement behavior has followed a well conceived and well implemented plan. In 1980, Kugler et al. (1980) created the current interest in the dynamic systems theory within the field of human motor behavior. From 1980 to 1988, the theoretical predictions of dynamic systems theory were investigated in the human movement behavior field of motor control. The theoretical concepts of self-organization, dynamic stability, and phase transitions have been experimentally tested and confirmed. As a result seven theoretical propositions for behavioral stability and change were put forth by Kelso and Schöner (Kelso & Schöner, 1987; Schöner & Kelso, 1988). In addition, Kelso, Schöner, Scholz, and Haken developed an experimental strategy for investigating coordinated biological movement (Kelso et al., 1987; Kelso & Schöner, 1988).

In the late 1980s, the use of dynamic systems theory moved into the field of motor development. Studies on infant treadmill walking, infant independent walking, and the transition from walking to running in infants have been conducted. In general, the predictions of dynamic systems theory for these coordinated movements have been confirmed. Of these studies, the work of Clark and Phillips (1993) most closely adhered to the experimental strategy for investigating coordinated behavior proposed by Kelso, Schöner, Scholz, and Haken (Kelso et al., 1987; Kelso & Schöner, 1988). Thus, this methodology is most closely followed in the present study.

In an independent line of investigation, one not related to dynamic systems theory, Alan Hreljac investigated possible determinants of the transition from walking to running in young adults. The researcher investigated metabolic, kinetic, and kinematic factors. With respect to dynamic systems theory, these factors may help in the identification of potential collective variables. Hreljac found only one variable that significantly determined the transition from walking to running: peak ankle angular velocity. With respect to dynamic systems theory, angular velocity is directly utilized in the development joint phase portraits and relative phase angle diagrams between joints. Hreljac's findings support the use of the collective variables of intralimb coordination selected for this study: relative phase angle between the ankle and knee, and relative phase angle between the ankle and hip.

CHAPTER THREE

METHODOLOGY

The specific protocol used in this study is presented within this chapter. The sample size, the characteristics of the subjects, the layout of the testing area, the locomotion trial procedure, and the methods of data reduction and analysis are presented.

Subjects

Forty subjects were recruited for this study. Twenty subjects (10 male, 10 female) were between 20 and 29 years of age (mean = 25 years) and 20 subjects (10 male, 10 female) were between 30 and 39 years of age (mean = 33 years). Data on subject age, height, weight, gender, and health status were gathered via a health screening questionnaire (Appendix A). Confidentiality of this information and the data collected during the videotaping testing session was maintained by assigning a unique identification number to each subject. Each subject had no known neurological, pathological, or musculoskeletal limitations which might have affected walking or running patterns of locomotion. Each subject completed and signed an Informed Consent Form (Appendix B).

Testing Area Layout

Data for this study were collected on videotape using a Panasonic AG-450 videocamera taping at 60 fields per second. Videotaping sessions were conducted in Room 208 of Spartan Complex Central at San Jose State University. Subjects were asked to perform walking and running trials along a painted black line on the floor (the walkway). Two 1.22 meter long, duct tape lines, that ran perpendicular to the long axis of the walkway, were placed 4.58 meters apart to indicate the area being videotaped during each locomotion trial. The Panasonic AG-450 videocamera, mounted on a tripod, was placed over a painted black line that ran perpendicular to the long axis of the walkway. This perpendicular line (PL) intersected the long axis of the walkway 2.29 meters from either end of the area being videotaped. The Panasonic AG-450 videocamera was placed over a point 6.10 meters from the intersection of PL and the long axis of the walkway. The optical axis of the Panasonic AG-450 videocamera was aligned parallel with PL. Three supplemental floodlights (Lowe DP, 750 watts) were located 3.05 meters from the long axis of the walkway. Two floodlights were placed 2.29 meters to the left of the PL and the third floodlight was placed 2.29 meters to the right of the PL. The supplemental floodlights were positioned to provide maximum illumination of the walkway. (see Figure 1).

<u>Locomotion Trial Procedure</u>

Subjects were scheduled for 45-minute testing sessions. They were asked to wear or bring a dark, short-sleeve shirt, dark shorts that did not hang below the knee, and walking/running shoes to the testing session. At the scheduled testing time, the experimenter met each subject at the east entrance of Spartan Complex Central. They then walked to Room 208. The experimenter began the session by explaining the testing procedure (Appendix C). The subject was asked to sign the Informed Consent Form (Appendix A) and to complete the health screening questionnaire (Appendix B). If required, the subject was given time to change clothes. The men's and women's bathrooms located outside the entrance to Gymnasium 44A were used for changing areas. Similar to Blanke and Hageman (1989), markers were placed on the right side of the body at the toe, heel, ankle, knee, hip, and shoulder joints of each subject. Two types of markers were used: reflective yellow tape attached to two-inch square pieces of cardboard and two-inch square pieces of black cardboard. Athletic tape was used to attach markers to skin or clothing. Double-sided mounting tape was used to attach markers to shoes. Reflective markers were used at the shoulder, hip, and knee. Reflective markers were used at the ankle, heel, and toe when shoes were predominantly black or a dark color. Black markers were used at the ankle, heel, and toe when shoes were predominantly white.

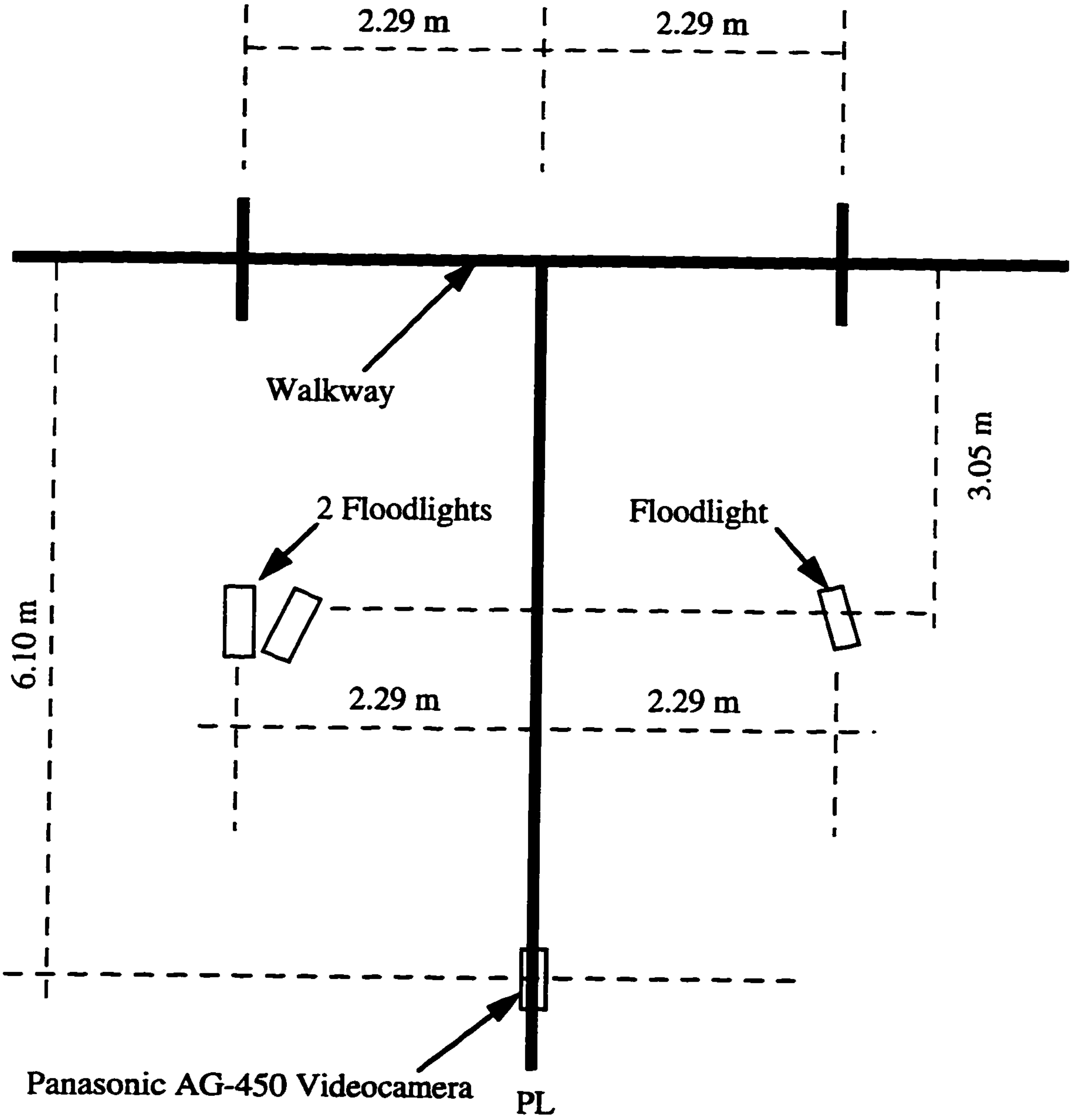


Figure 1. Test Area Layout

After placing the joint markers on the subject, the recording function of the Panasonic AG-450 videocamera was activated. The experimenter familiarized the subject with the layout of the testing area and reminded the subject that four walking trials and four running trials would be performed and that the experiment could be stopped at any time. The subject was allowed to perform three practice walking trials, one at each speed, and three practice running trials, one at each speed, before the actual testing began.

After completing the practice trials, the subject was handed a one-meter stick and asked to hold the stick parallel to the long axis of the walkway while standing at the intersection of PL and the long axis of the walkway. The videotaped one-meter stick was used during the digitizing phase of data reduction to determine the scale factor. Similar to Leiper & Craik (1991), the first trial was videotaped at a walking speed. The experimenter gave the instruction for the normal walking trial (i.e., "walk at your preferred or normal speed of walking") and then the subject performed the trial. After completing the normal walking trial, the subject was instructed to perform the slow walking trial. This was followed by another normal walking trial, and then the fast walking trial. The running trials were conducted in a similar order: normal running trial, slow running trial, normal running trial, and fast running trial. A trial was deemed acceptable if the subject performed two right foot contacts within the area being videotaped. If a trial was determined to be unacceptable, the experimenter asked the subject to repeat the trial.

Data Reduction and Analysis

The videotaped locations of the right toe, heel, ankle, knee, hip, and shoulder joint markers were converted into numerical x-y coordinate data using Peak Performance Technologies' Peak5 Motion Measurement System (the Peak system). The Peak system consists of an HIQ, IBM-486AT compatible computer running the Peak5 2D-motion measurement software, an Impression 3 Plus computer monitor, a Panasonic CT-1400MG color video monitor, and a Panasonic AG-6300 video cassette recorder. For each locomotion trial, the x-y coordinate position of each joint marker was digitized frame-by-frame for the stride cycle that began with the right foot heel-strike on the start side of the intersection of PL and the long axis of the walkway, and ended with the right foot heel-strike on the finish side. Experimenter digitizing reliability (r = 0.88) was determined using the split-half method (Thomas & Nelson, 1990) on twelve digitizing trials of a one-meter stick. The raw, digitized data were smoothed using a Butterworth filter set at the optimal frequency. After data smoothing, angular displacement and angular velocity at the hip, knee, and ankle, and horizontal velocity at the hip were calculated. These data were then converted into a Microsoft Excel 5.0 file for further analysis on a 6110CD Macintosh Power PC computer.

As described by Clark and Phillips (1993), hip, knee and ankle angular displacement and angular velocity data for each frame of the stride cycle were converted into joint phase angles by using the following equation: $\phi = \tan^{-1}(\dot{x}/x)$. Where, x represents angular displacement and $\dot{x}$ represents angular velocity. The relative phase angle between hip rotation and ankle rotation for each frame of the stride cycle was then calculated as: $\phi_{rel.phase} = \phi_{hip} - \phi_{ankle}$. The relative phase angle between the knee and the ankle was calculated in a similar manner. The relative phase angles of the hip and ankle as a percentage of the stride cycle and the relative phase angles of the knee and ankle as a percentage of stride cycle were calculated for each locomotion trial. The stride cycle was defined as the time between consecutive right foot heel-strikes. Relative phase angle versus percentage of stride cycle plots were created for the different age groups, different gender groups, and different locomotion trials.

After an extensive review of the literature on dynamic systems theory and its applications in the fields of motor control, motor learning, and motor development, a quantitative method for testing the similarities or differences between relative phase angle plots was not located (Clark & Phillips, 1993; Clark et al., 1988, 1990; Thelen, 1986; Thelen & Ulrich, 1991; Thelen et al., 1987). Therefore, only qualitative comparisons were used to determine the similarities and differences between the relative phase angle plots. To test the prediction of Hreljac (1995a) that peak ankle angular velocity during slow running is less than peak ankle angular velocity during fast walking, one traditional kinematic parameter was quantitatively analyzed: peak ankle angular velocity. Descriptive statistics were used to determine means and standard deviations for speed of locomotion during each type of walking trial (slow, normal, and fast walking; slow, normal, and fast running). Descriptive statistics were also used to determine means and standard deviations for peak ankle angular velocity by age group, gender group, and speed of locomotion. Separate 2 (age) x 2 (gender) x 8 (trial) factorial ANOVAs with repeated measures on the last factor were performed to identify statistically significant differences in horizontal velocity and peak ankle angular velocity. If a statistically significant difference was found, a Newman-Keuls post hoc comparison was performed (Thomas & Nelson, 1990).

Summary

In this chapter, the experimental methodology that was employed during this study was presented. The subject selection criteria, the layout of the testing area, and the procedures that were followed during data collection were described. The methods used for the reduction of the collected data and for their subsequent analysis were presented. A dynamic systems analysis and a traditional kinematic gait analysis were performed. The relative phase angle diagrams, which summarize the dynamic systems analysis, and the appropriate statistical evaluation method for the kinematic gait analysis were described.

CHAPTER 4

RESULTS

Results of the data analysis are presented in this chapter. These results address the three purposes of this study. The primary purpose was to compare the attractor states of the two collective variables of locomotion during four trials of walking and four trials of running. The secondary purpose was to compare the attractor states of the two collective variables of locomotion for a group of 20-29 year old adults and a group of 30-39 year old adults during walking and during running. The tertiary purpose was to compare peak ankle angular velocity during the fast walking trials with peak ankle angular velocity during the slow running trials.

In the first section of this chapter, the results of a 2 (age) x 2 (gender) x 8 (trial) factorial ANOVA comparing mean values of horizontal velocity of locomotion are presented. In the next three sections, the results of the dynamic systems theory analysis of walking and running are presented. The results of the dynamic systems theory analysis comparing the walking and running patterns of 20-29 year old adults and 30-39 year old adults are presented in the following two sections. These two sections are followed by the results of a 2 (age) x 2 (gender) x 8 (trial) factorial ANOVA comparing mean values of peak ankle angular velocity. In the final section of this chapter, the overall findings of this study based on the results of the data analysis are presented.

Horizontal Velocity

Mean values for horizontal velocity during each locomotion trial are presented in Table 1. Results from a 2 (age) x 2 (gender) x 8 (trial) factorial ANOVA indicated significant main effects for gender, $F(1,36) = 4.07$, $p < .05$, and trial, $F(7,266) = 471.47$, $p < .001$, and a significant interaction effect for gender and trial, $F(7, 252) = 2.68$, $p < .01$. All other effects were not statistically significant ($p > .05$). Collapsed over trials, mean horizontal velocity for males (2.597 m/s) was significantly

Table 1

<u>Mean Values for Horizontal Velocity (m/s)</u>

	N Walking 1	S Walking	N Walking 2	F Walking	N Running 1	S Running	N Running 2	F Running
20-29 (male)	1.605	1.097	1.548	2.185	3.717	2.452	3.528	4.879
20-29 (female)	1.483	1.031	1.413	1.967	3.221	2.295	3.076	4.282
30-39 (male)	1.646	1.175	1.614	2.124	3.463	2.596	3.360	4.557
30-39 (female)	1.640	1.251	1.560	2.060	3.421	2.534	3.266	4.089

greater than the mean horizontal velocity for females (2.412 m/s). The results of a Newman-Keuls post hoc comparison indicated horizontal velocity of each locomotion trial was significantly different from horizontal velocity of every other locomotion trial except for the two normal walking trials. The interaction effect between gender and trial is presented on Figure 2. Because the significant interaction is disordinal, the main effect for gender cannot be unambiguously interpreted.

Comparing the Four Locomotion Trials for Walking

Displayed on Figure 3 are the composite hip-ankle relative phase angle diagrams of the entire subject pool for each locomotion trial of walking. Despite the fact that apparent variations exist between the individual diagrams for each locomotion trial, each diagram exhibits a similar overall pattern during the stride cycle. Dynamic systems theory predicts that variations will exist as the value of the control parameter is increased; but, each experimental trial should demonstrate the same general pattern (Thelen, 1989). The composite knee-ankle relative phase angle diagrams of the entire subject pool for each locomotion trial of walking are displayed on Figure 4. Inspection of this figure also reveals a similar overall pattern for each walking trial. Gender comparisons for each age group are presented on Figures 5 through 8. A similar overall pattern for the attractor state of walking is evident for both genders in both age groups.

Comparing the Four Locomotion Trials for Running

The composite hip-ankle relative phase angle diagrams of the entire subject pool for each locomotion trial of running are presented on Figure 9. It can be seen, that a similar overall pattern exists for each running trial. Displayed on Figure 10 are the composite knee-ankle relative phase angle diagrams of the entire subject pool for each locomotion trial of running. This figure also reveals a similar overall pattern for each running trial. Gender comparisons for each age group are presented on Figures 11 through 14. A similar overall pattern for the attractor state of running is evident for both genders in both age groups.

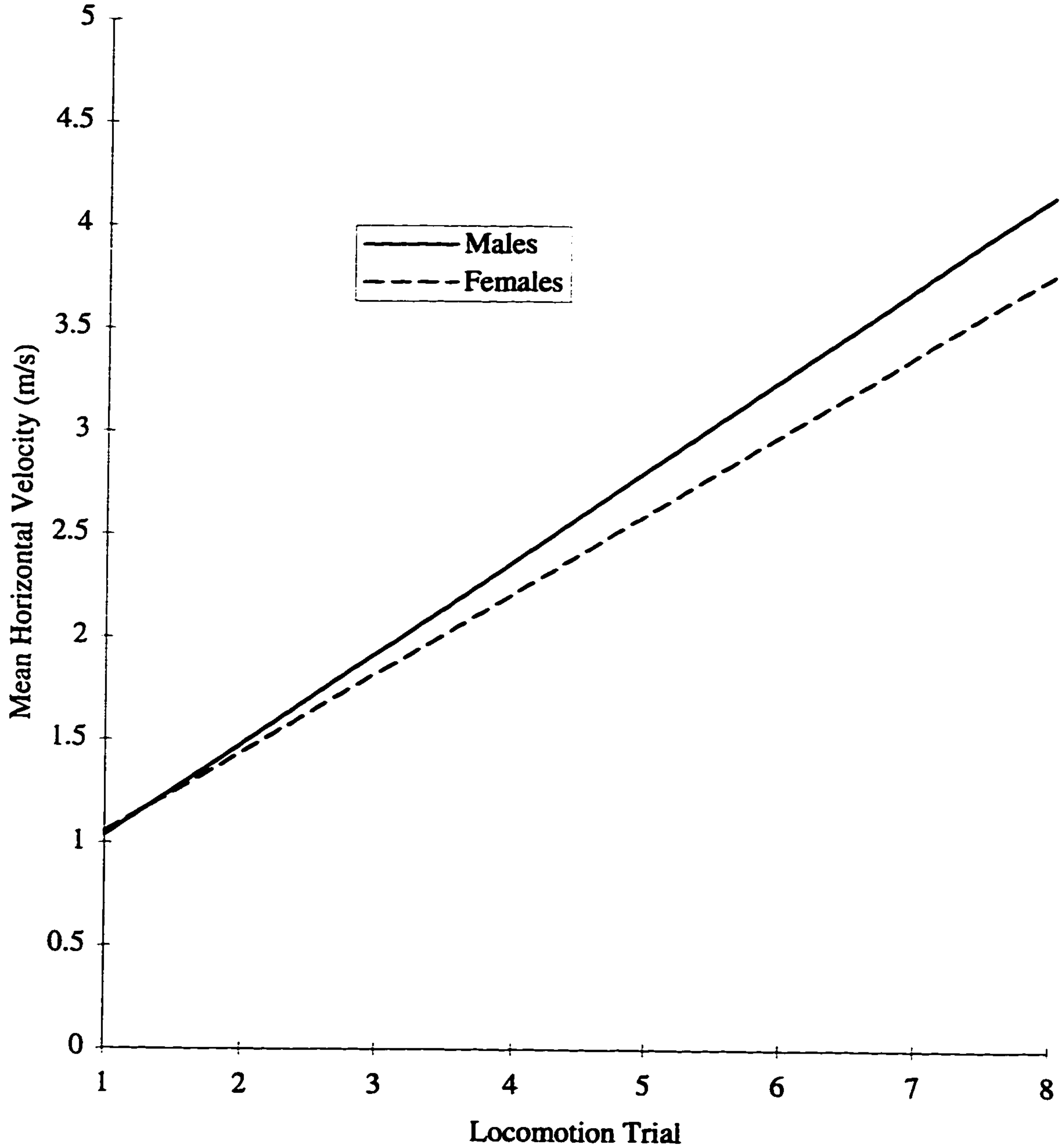


Figure 2. Interaction Between Gender and Locomotion Trial for Mean Horizontal Velocity

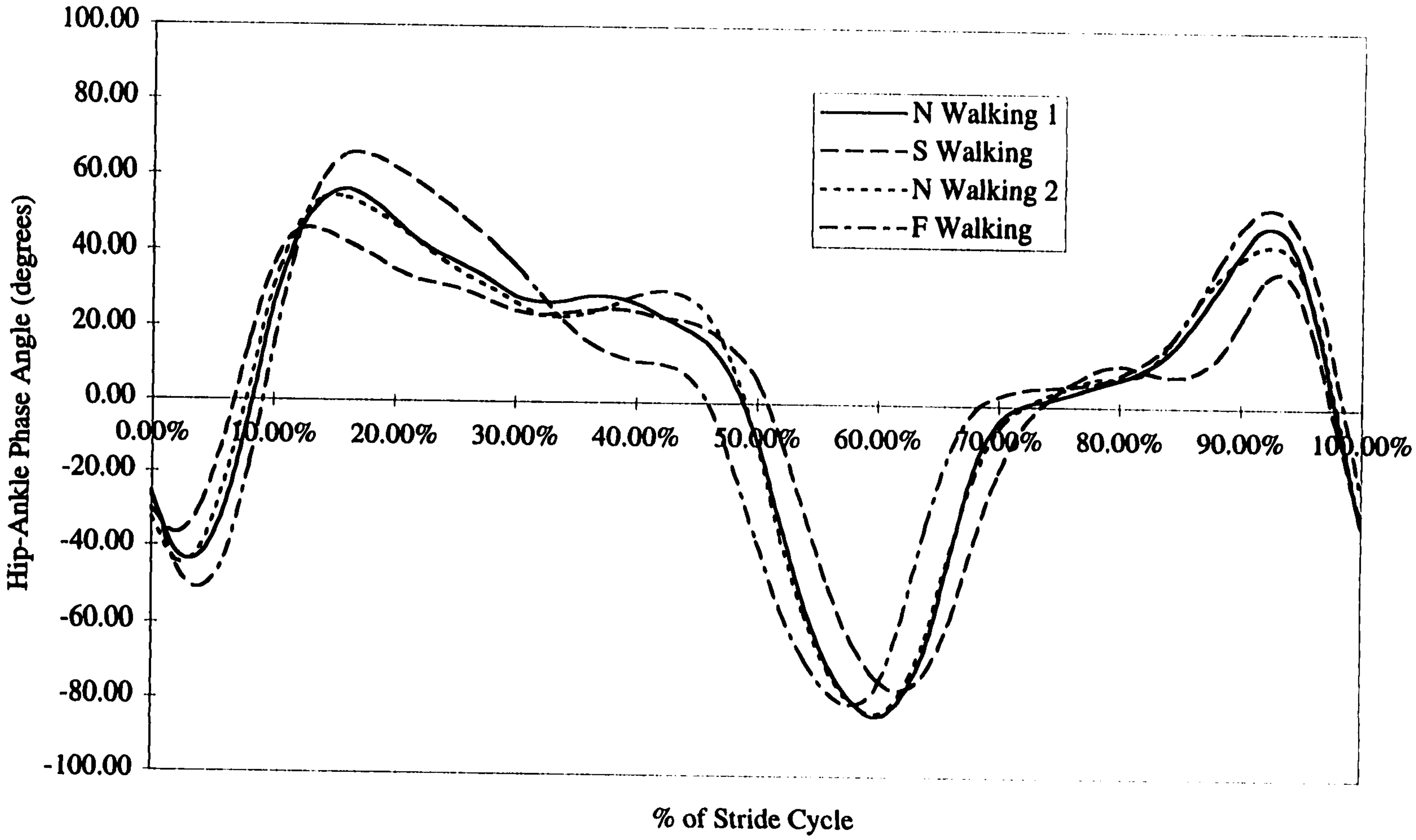


Figure 3. Comparison of Walking Trials for the Hip-Ankle Phase Angle

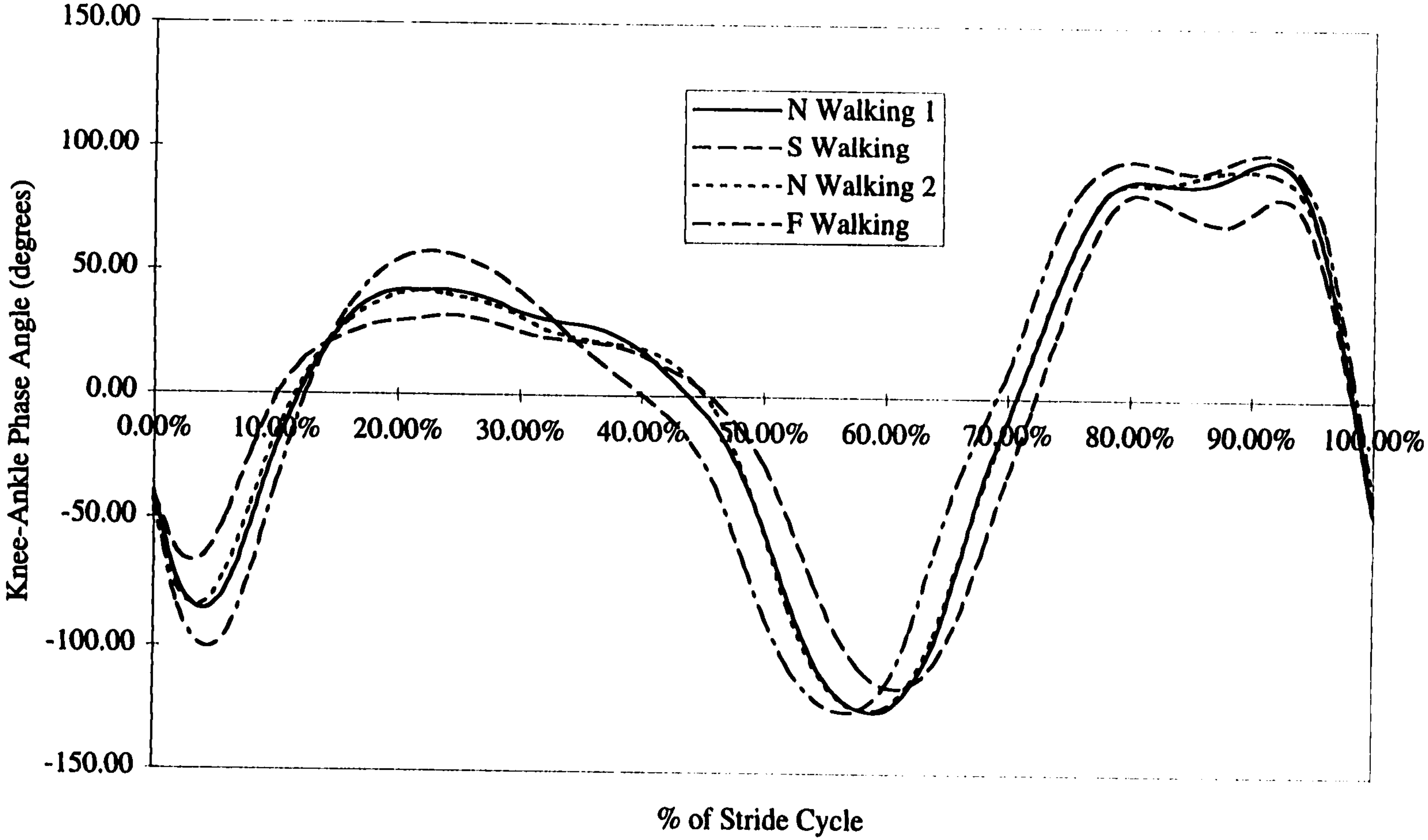


Figure 4. Comparison of Walking Trials for the Knee-Ankle Phase Angle

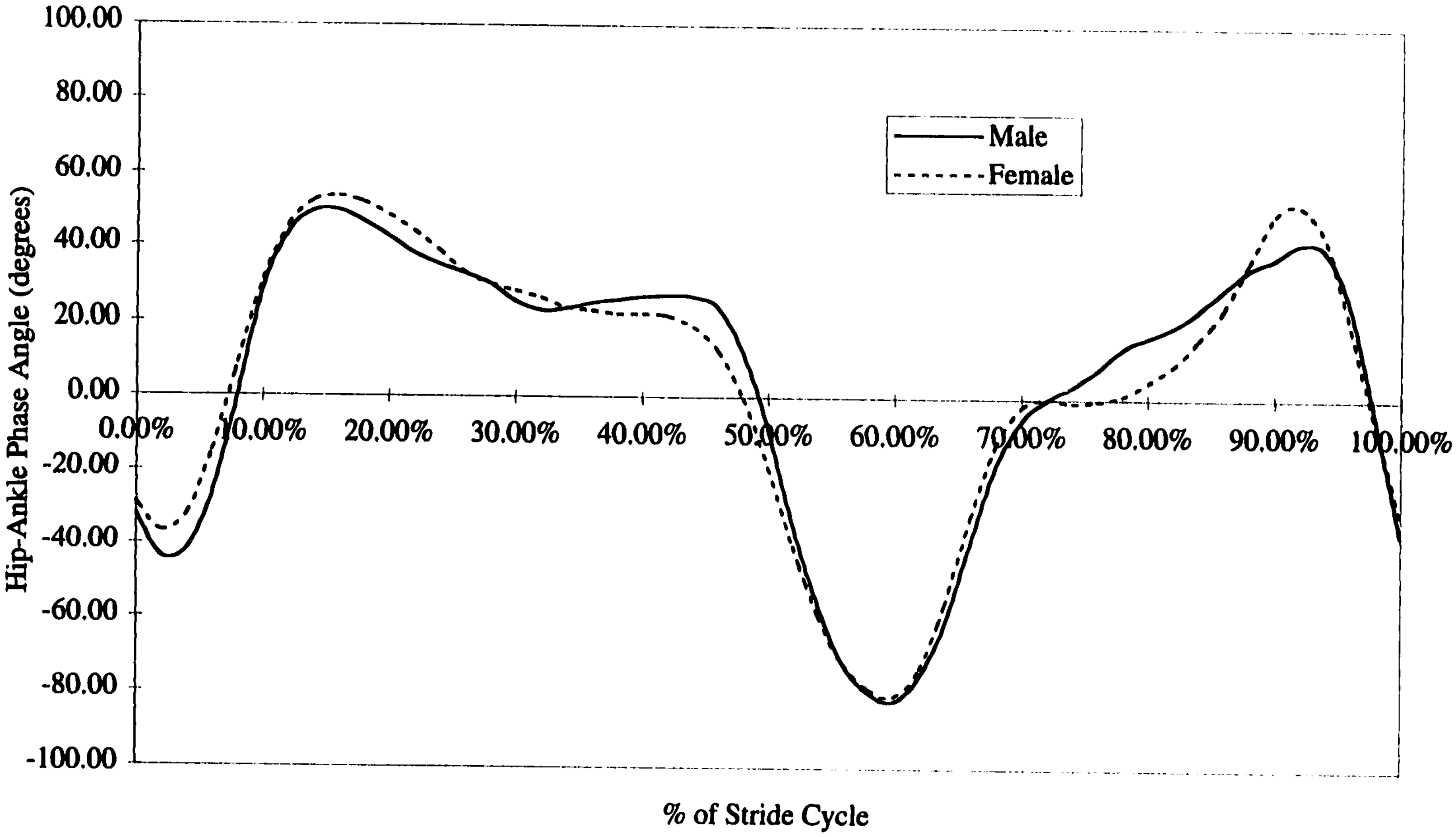


Figure 5. Normal Walking Trial Comparison of the 20-29 Males vs. the 20-29 Females for the Hip-Ankle Phase Angle

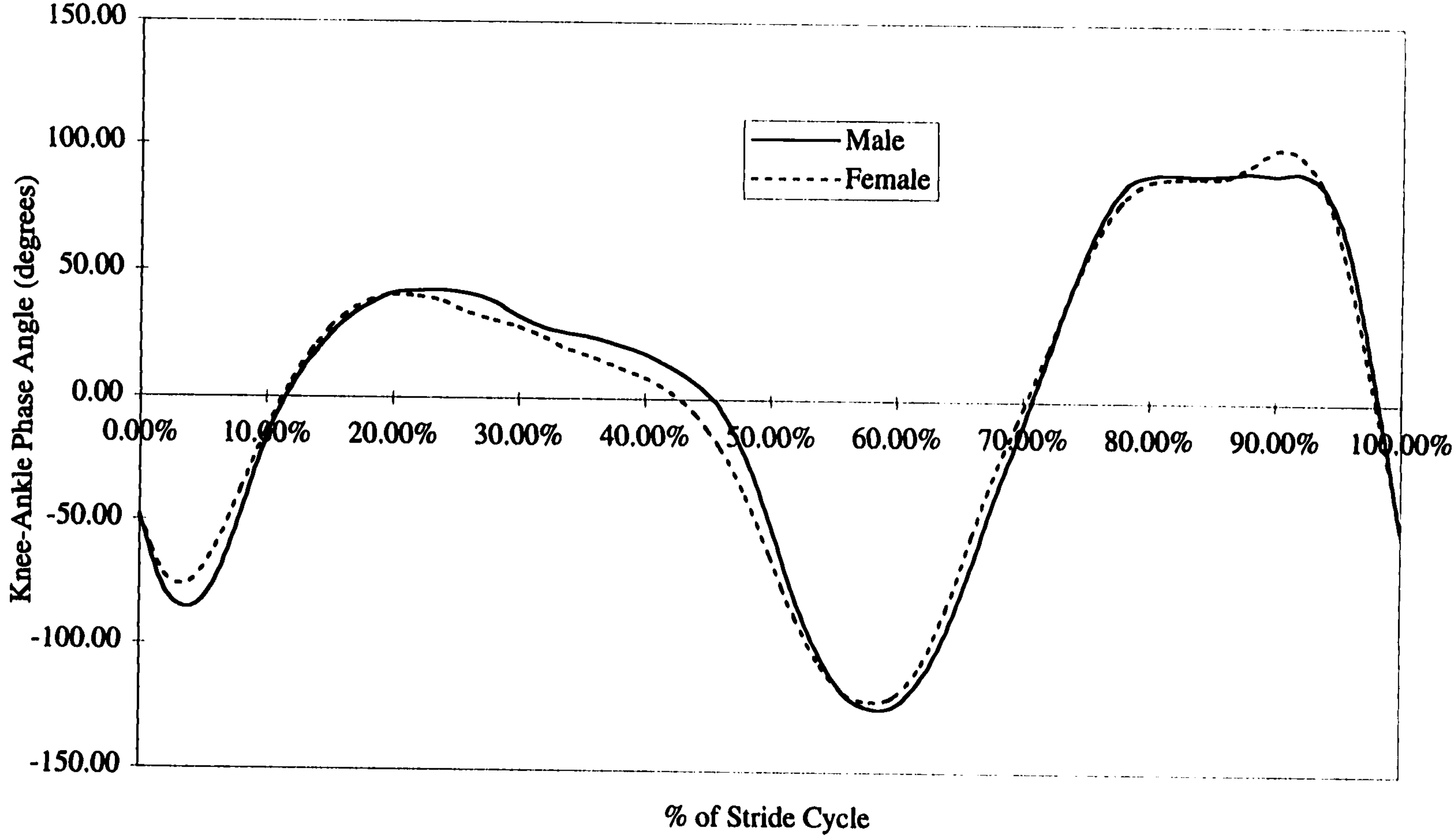


Figure 6. Normal Walking Trial Comparison of the 20-29 Males vs. the 20-29 Females for the Knee-Ankle Phase Angle

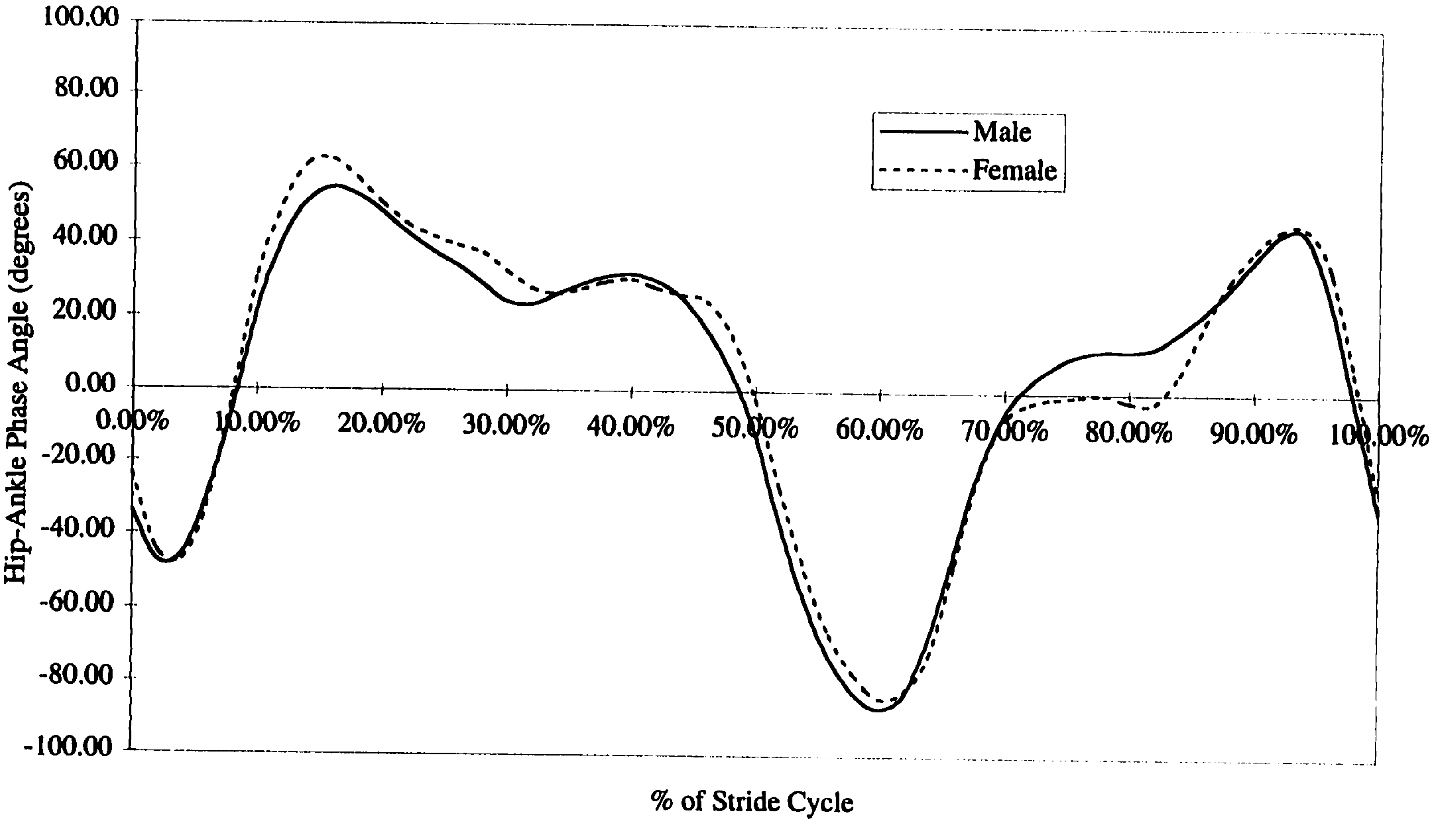


Figure 7. Normal Walking Trial Comparison of the 30-39 Males vs. the 30-39 Females for the Hip-Ankle Phase Angle

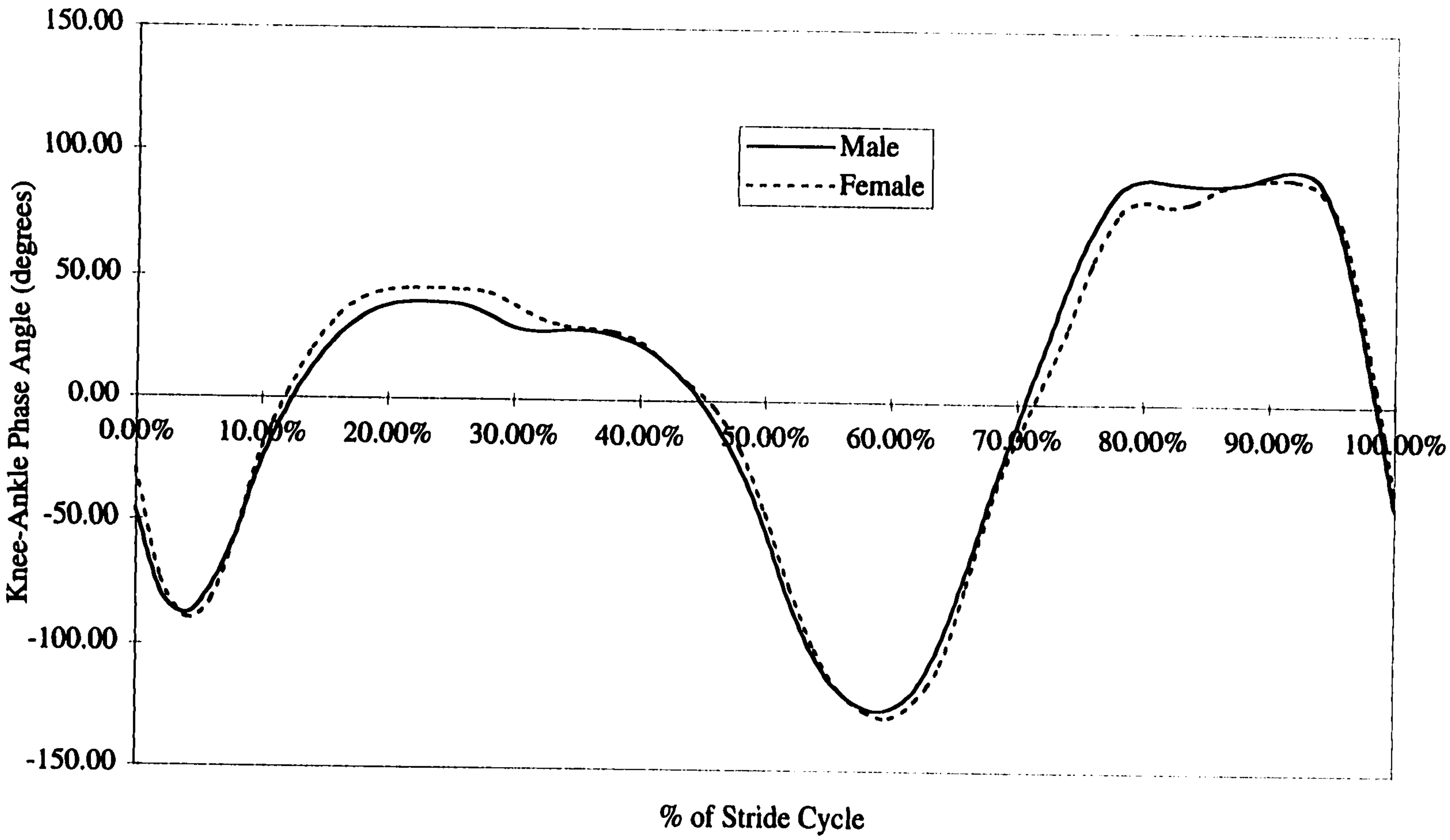


Figure 8. Normal Walking Trial Comparison of the 30-39 Males vs. the 30-39 Females for the Knee-Ankle Phase Angle

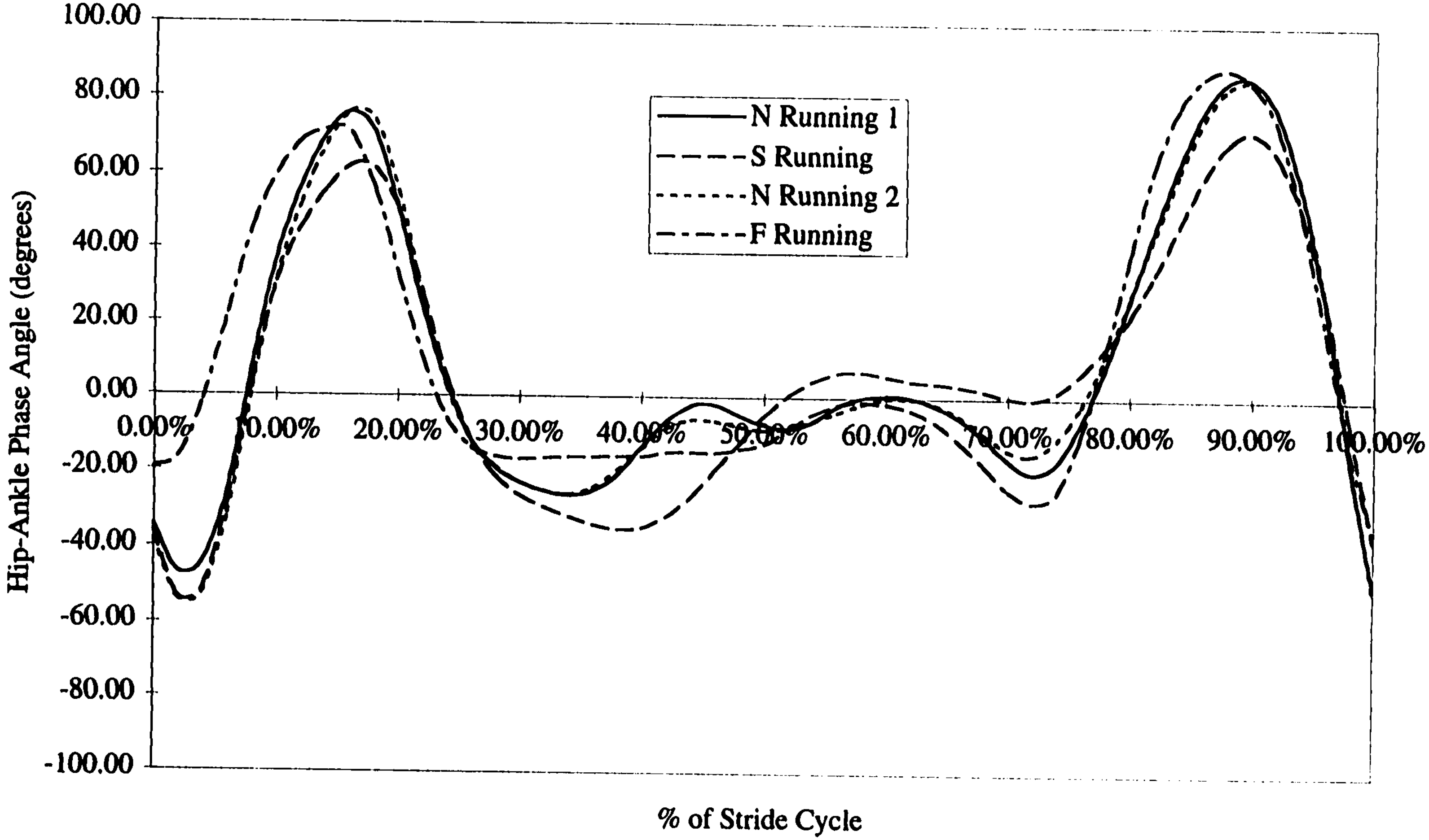


Figure 9. Comparison of Running Trials for the Hip-Ankle Phase Angle

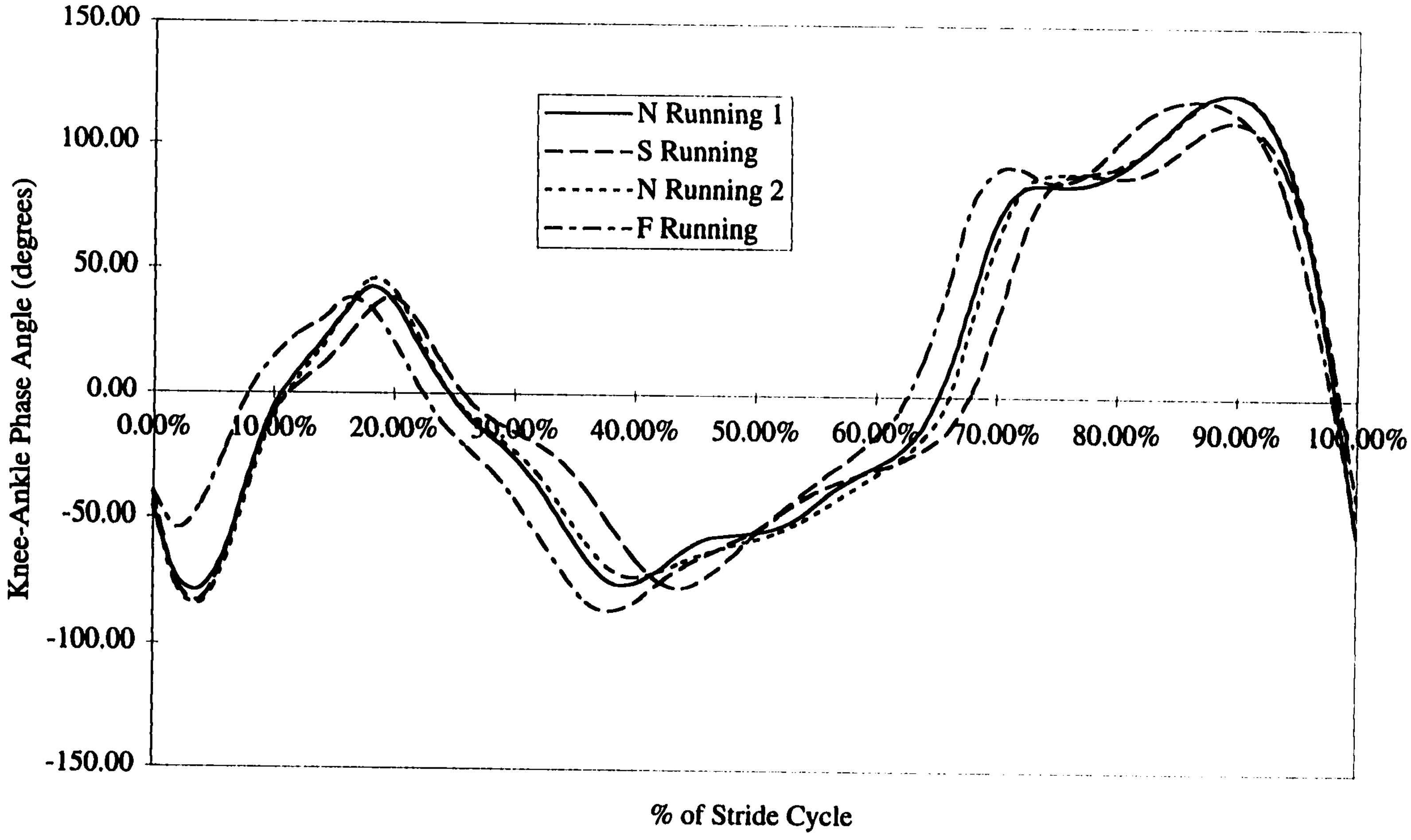


Figure 10. Comparison of Running Trials for the Knee-Ankle Phase Angle

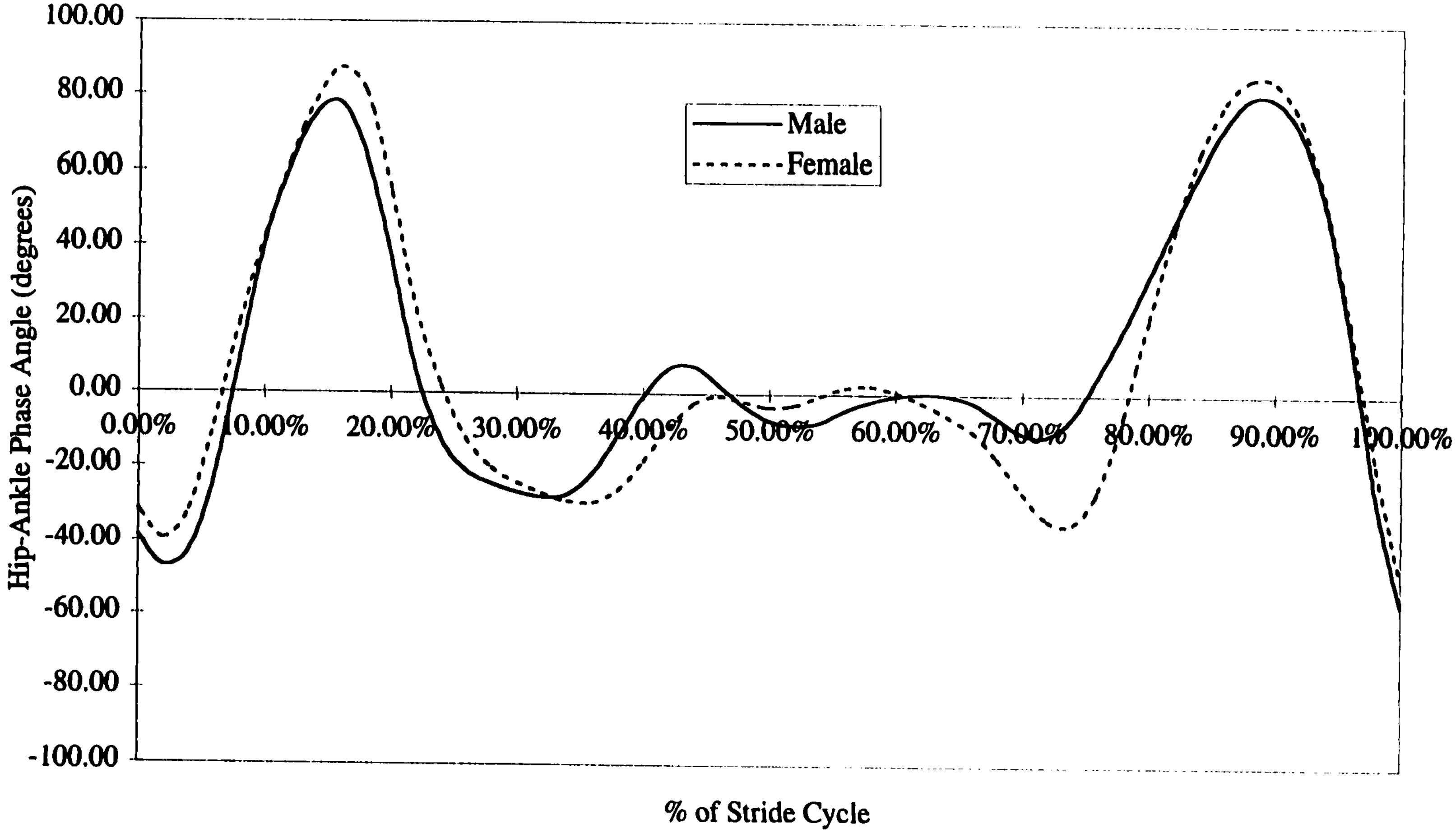


Figure 11. Normal Running Trial Comparison of the 20-29 Males vs. the 20-29 Females for the Hip-Ankle Phase Angle

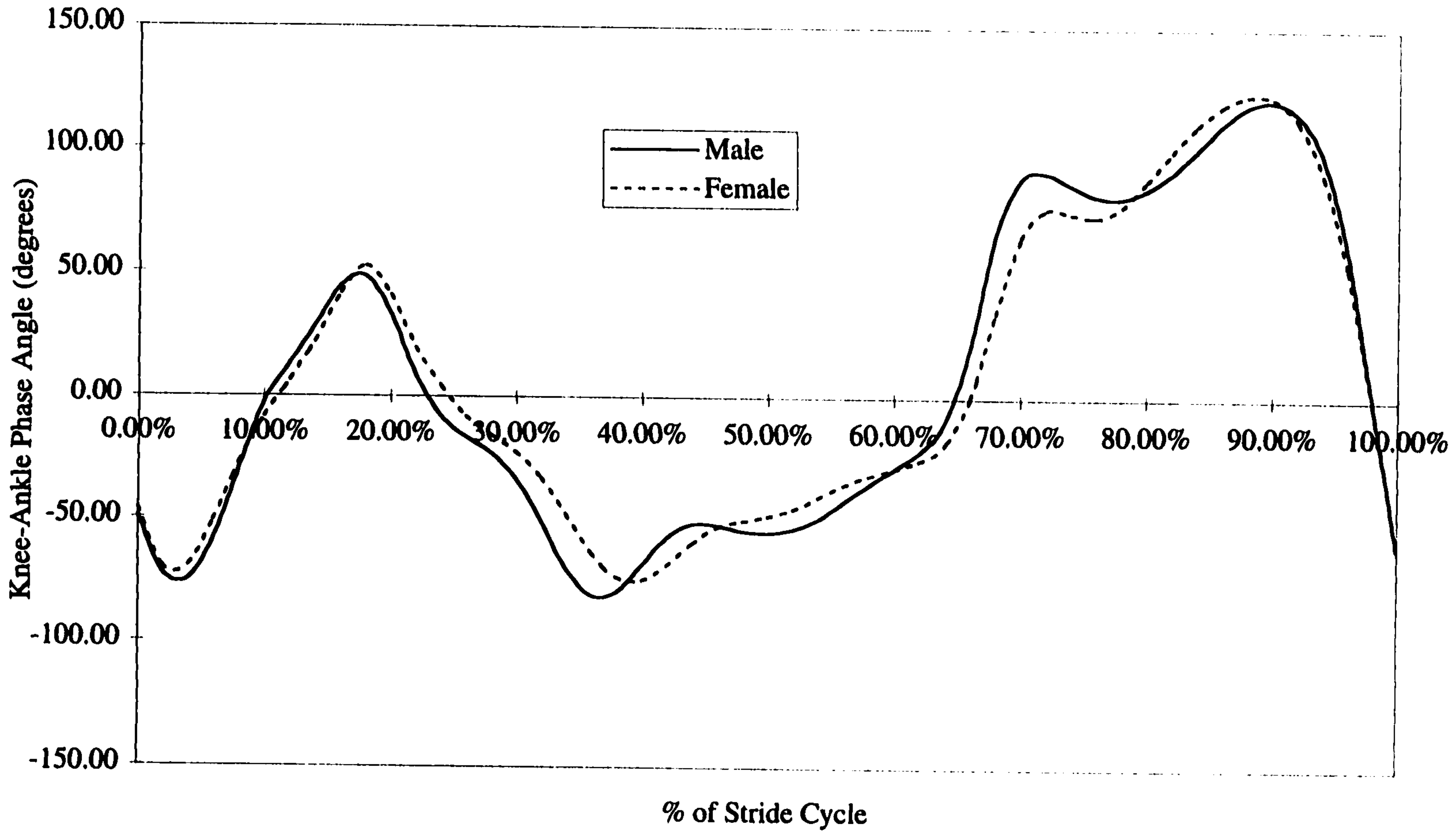
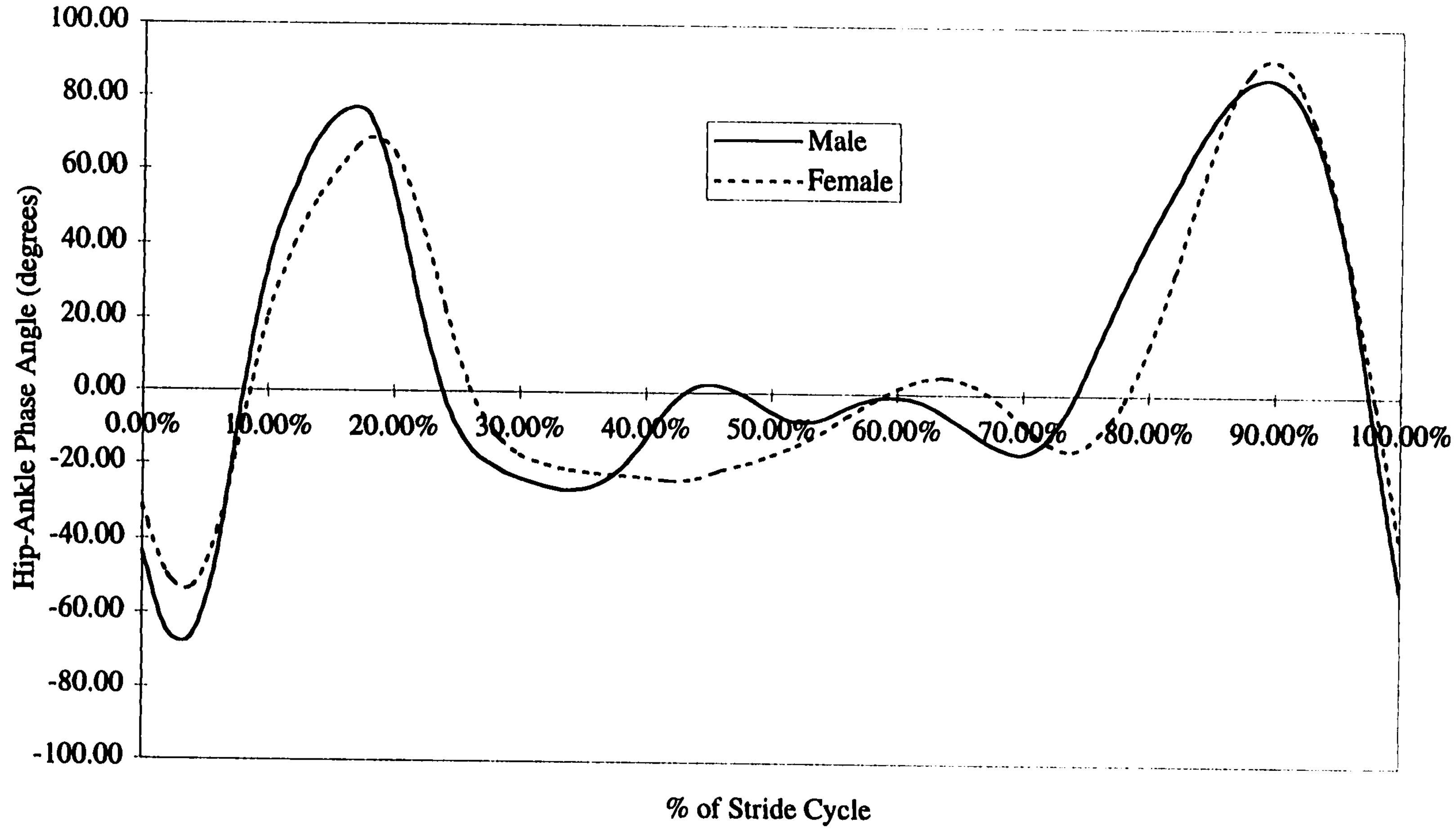


Figure 12. Normal Running Trial Comparison of the 20-29 Males vs. the 20-29 Females for the Knee-Ankle Phase Angle



<u>Figure 13.</u> Normal Running Trial Comparison of the 30-39 Males vs. the 30-39 Females for the Hip-Ankle Phase Angle

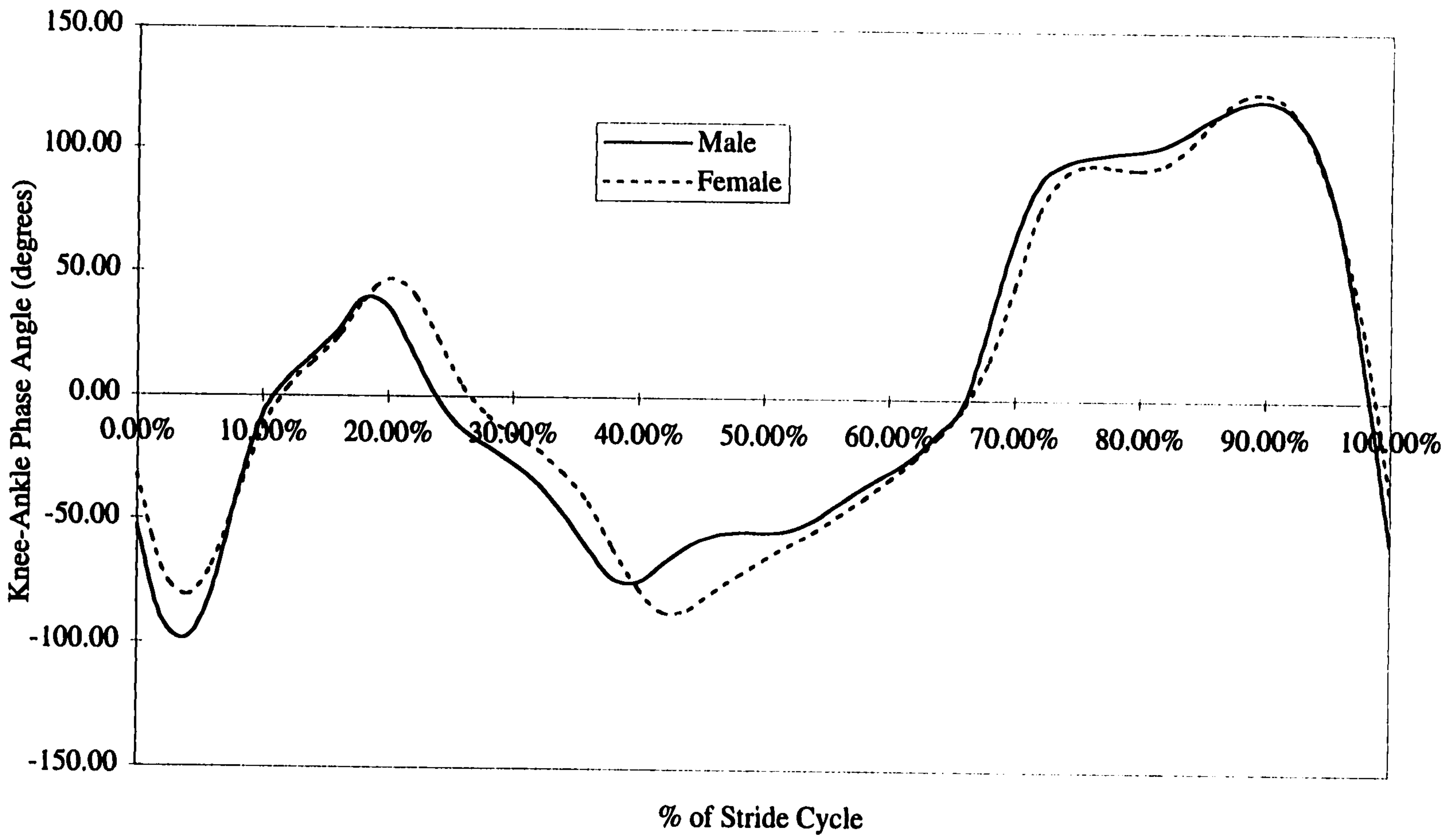


Figure 14. Normal Running Trial Comparison of the 30-39 Males vs. the 30-39 Females for the Knee-Ankle Phase Angle

Comparing Walking and Running

A comparison between the composite hip-ankle relative phase angle diagrams of the entire subject pool for the two normal walking trials and the two normal running trials is displayed on Figure 15. An apparent difference in the overall patterns of these two diagrams can be seen. Displayed on Figure 16 is a comparison between the composite hip-ankle relative phase angle diagrams of the entire subject pool for the fast walking trial and the slow running trial. Once again, an apparent difference in the overall patterns can be seen.

A comparison between the composite knee-ankle relative phase angle diagrams of the entire subject pool for the two normal walking trials and the two normal running trials is displayed on Figure 17. An apparent difference in the overall patterns of these diagrams can be seen. On Figure 18, a comparison between the composite knee-ankle relative phase angle diagrams of the entire subject pool for the fast walking trial and the slow running trial is presented. Once again, an apparent difference in the overall patterns of these diagrams can be seen.

Plots comparing the composite hip-ankle relative phase angle diagrams of the normal walking trials for the 20-29 age group and the 30-39 age group are displayed on Figure 19. A similar overall pattern for each age group can be seen in this figure. A comparison of composite knee-ankle relative phase angle diagrams during normal walking trials for the 20-29 age group and the 30-39 age group is presented on Figure 20. This figure also reveals a similar overall pattern for each age group.

A comparison of composite hip-ankle relative phase angle diagrams of the normal running trials for the 20-29 age group and the 30-39 age group is presented on Figure 21. Inspection of this figure reveals a similar overall pattern for each age group. Displayed on Figure 22 is a comparison between the composite knee-ankle relative phase angle diagrams

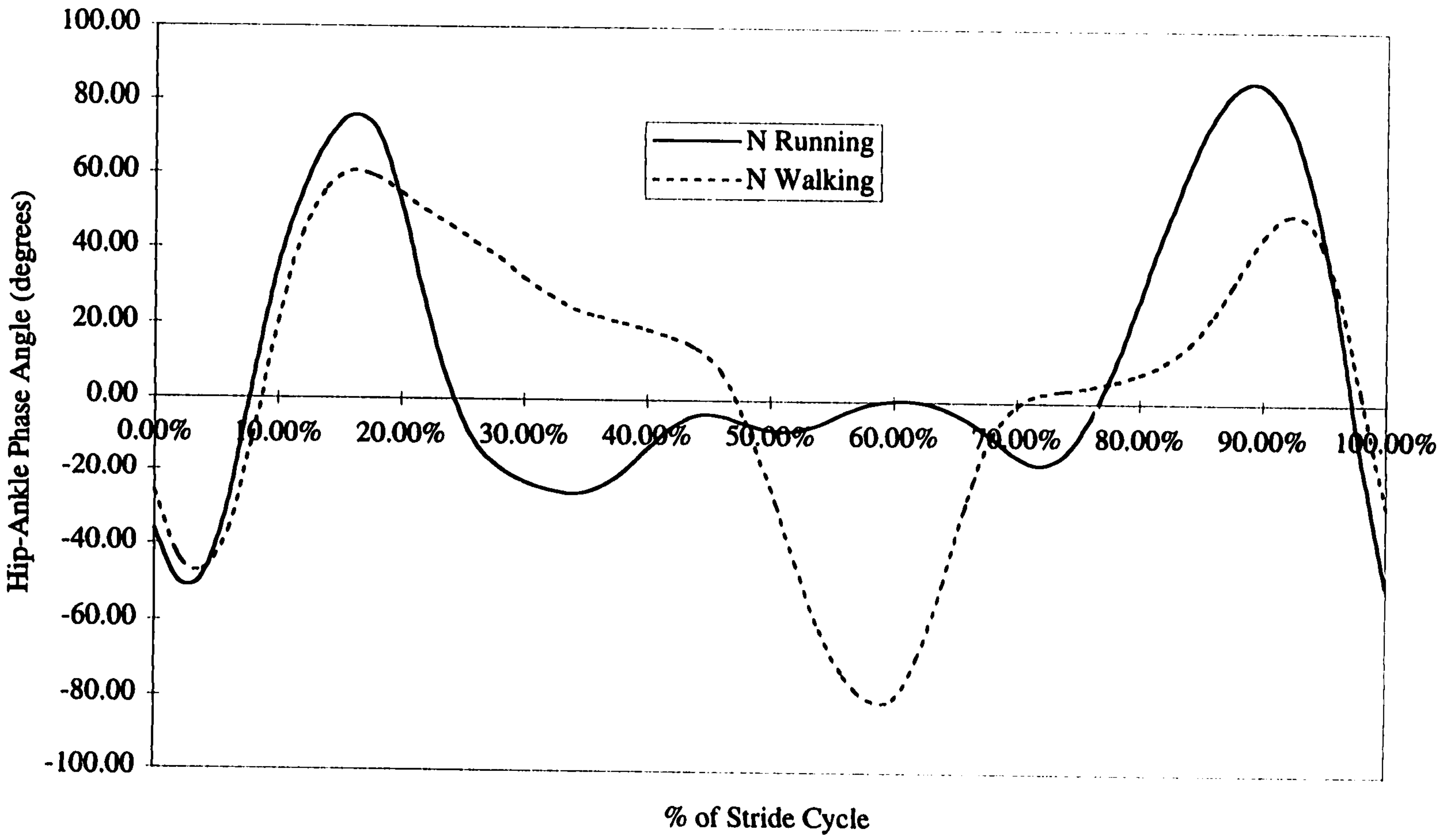


Figure 15. Walk-Run Comparison of Normal Running vs. Normal Walking Trials for the Hip-Ankle Phase Angle

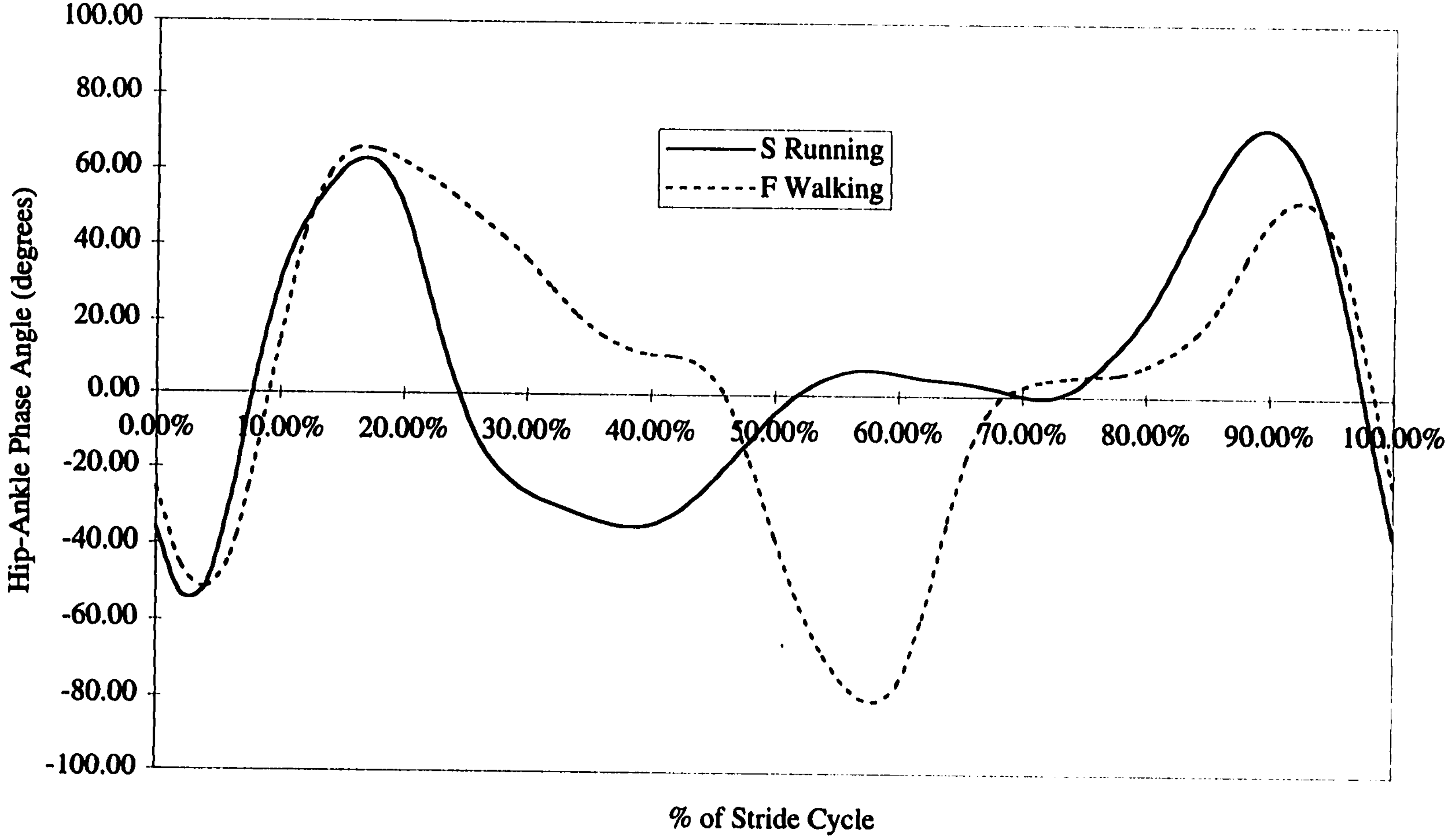


Figure 16. Walk-Run Comparison of Slow Running vs. Fast Walking Trials for the Hip-Ankle Phase Angle

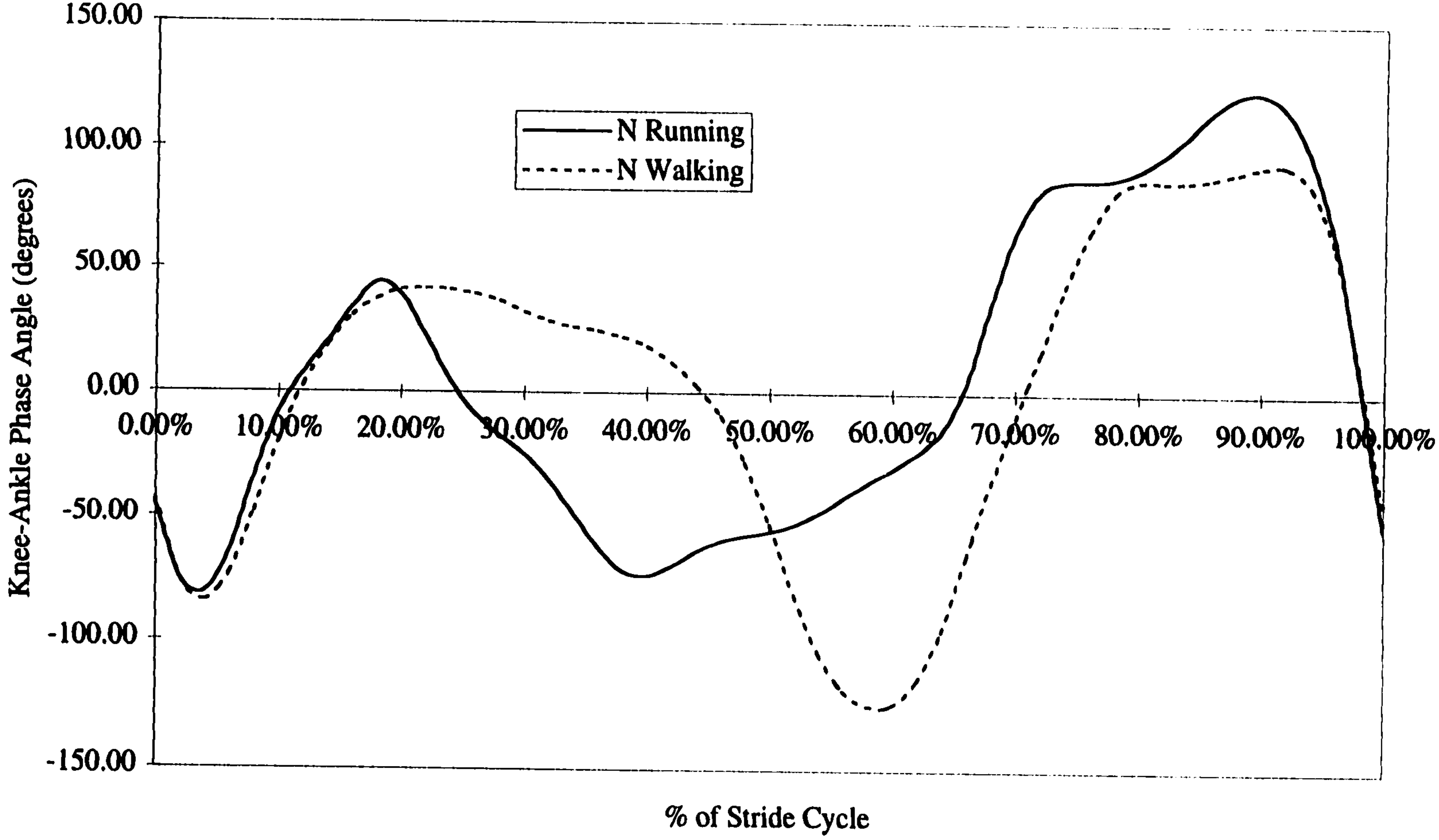
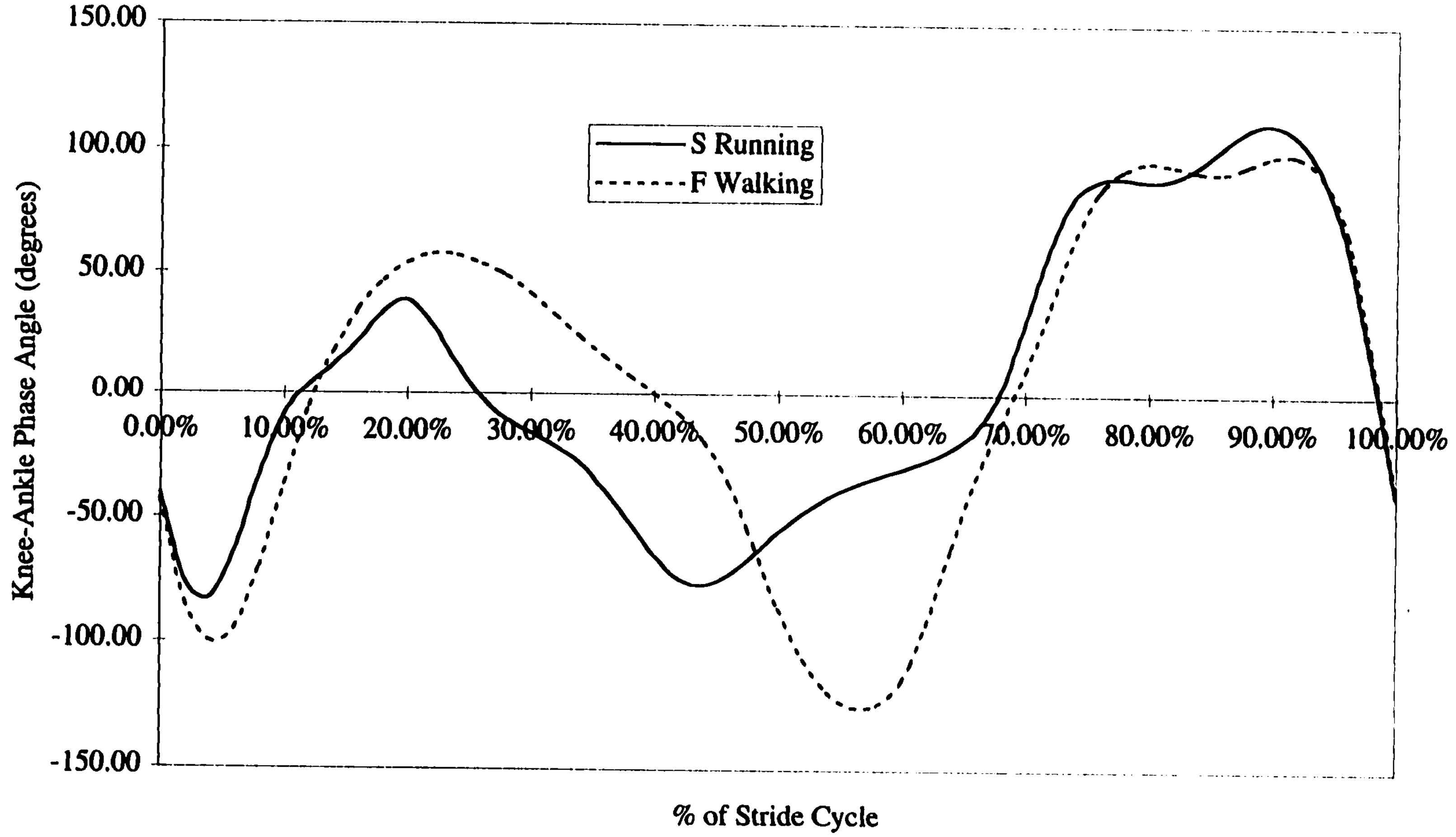


Figure 17. Walk-Run Comparison of Normal Running vs. Normal Walking Trials for the Knee-Ankle Phase Angle



<u>Figure 18.</u> Walk-Run Comparison for Slow Running vs. Fast Walking Trials for the Knee-Ankle Phase Angle

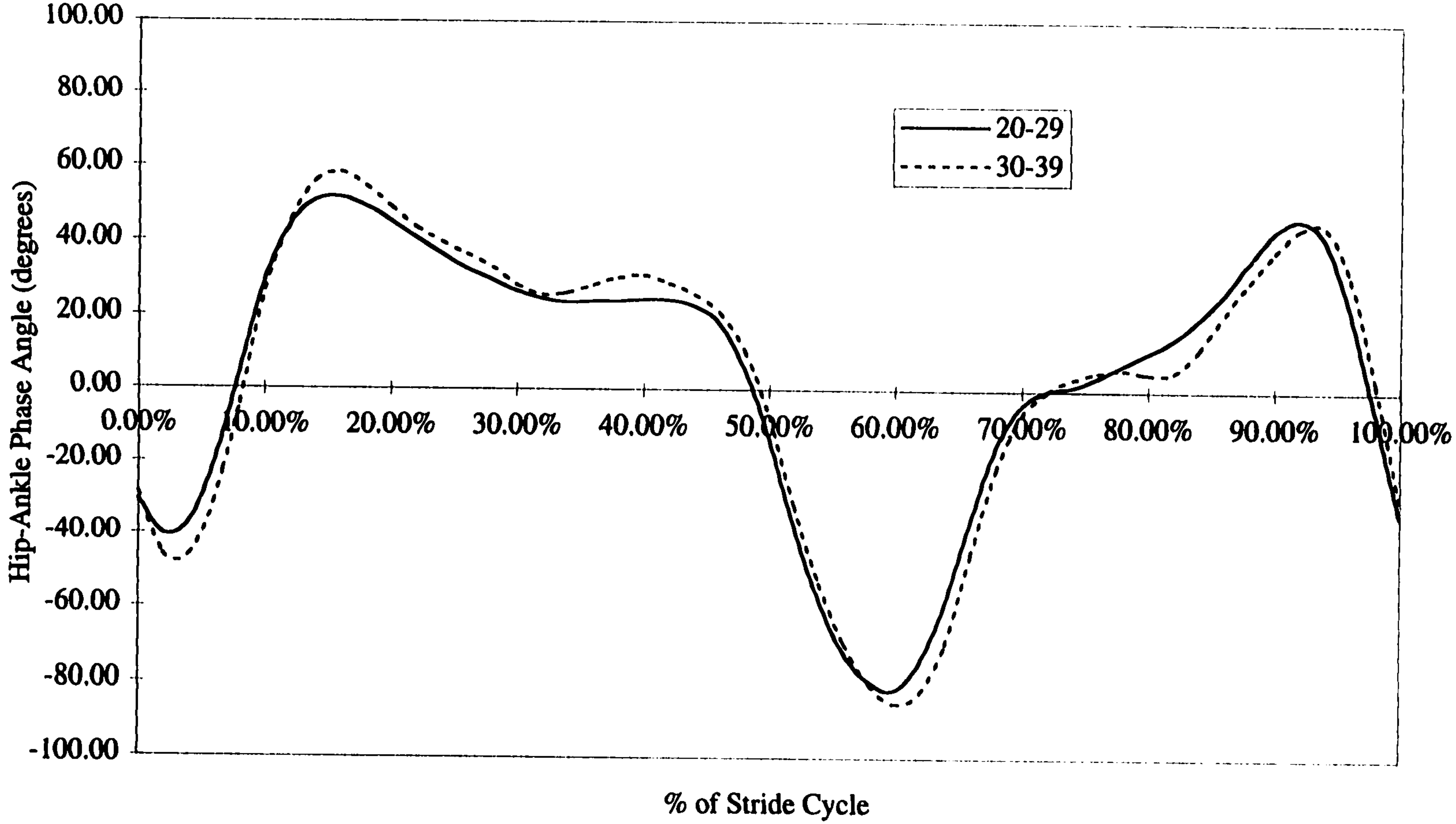


Figure 19. Normal Walking Trial Comparison of the 20-29 Age Group vs. the 30-39 Age Group for the Hip-Ankle Phase Angle

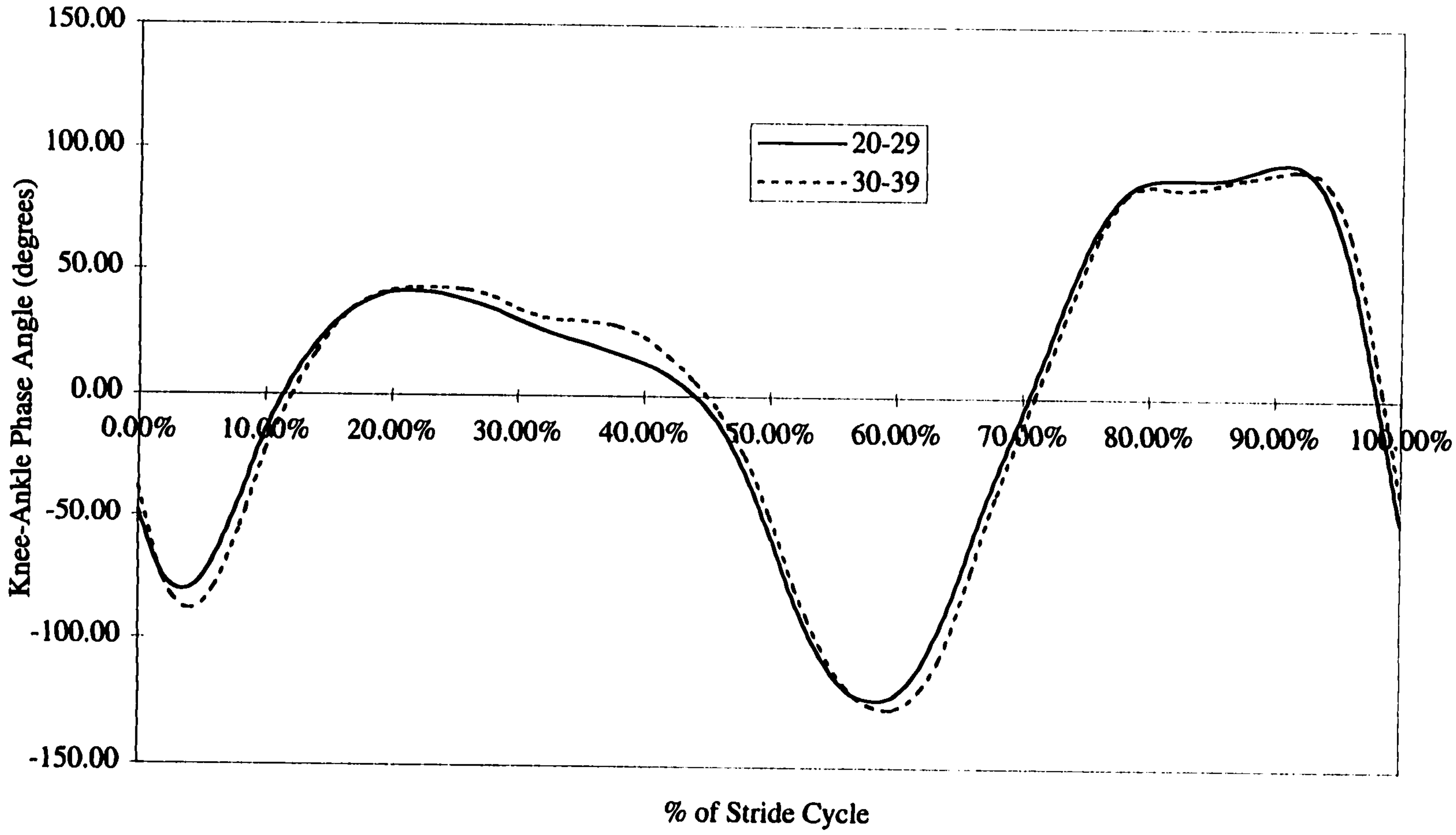


Figure 20. Normal Walking Trial Comparison of the 20-29 Age Group vs. the 30-39 Age Group for the Knee-Ankle Phase Angle

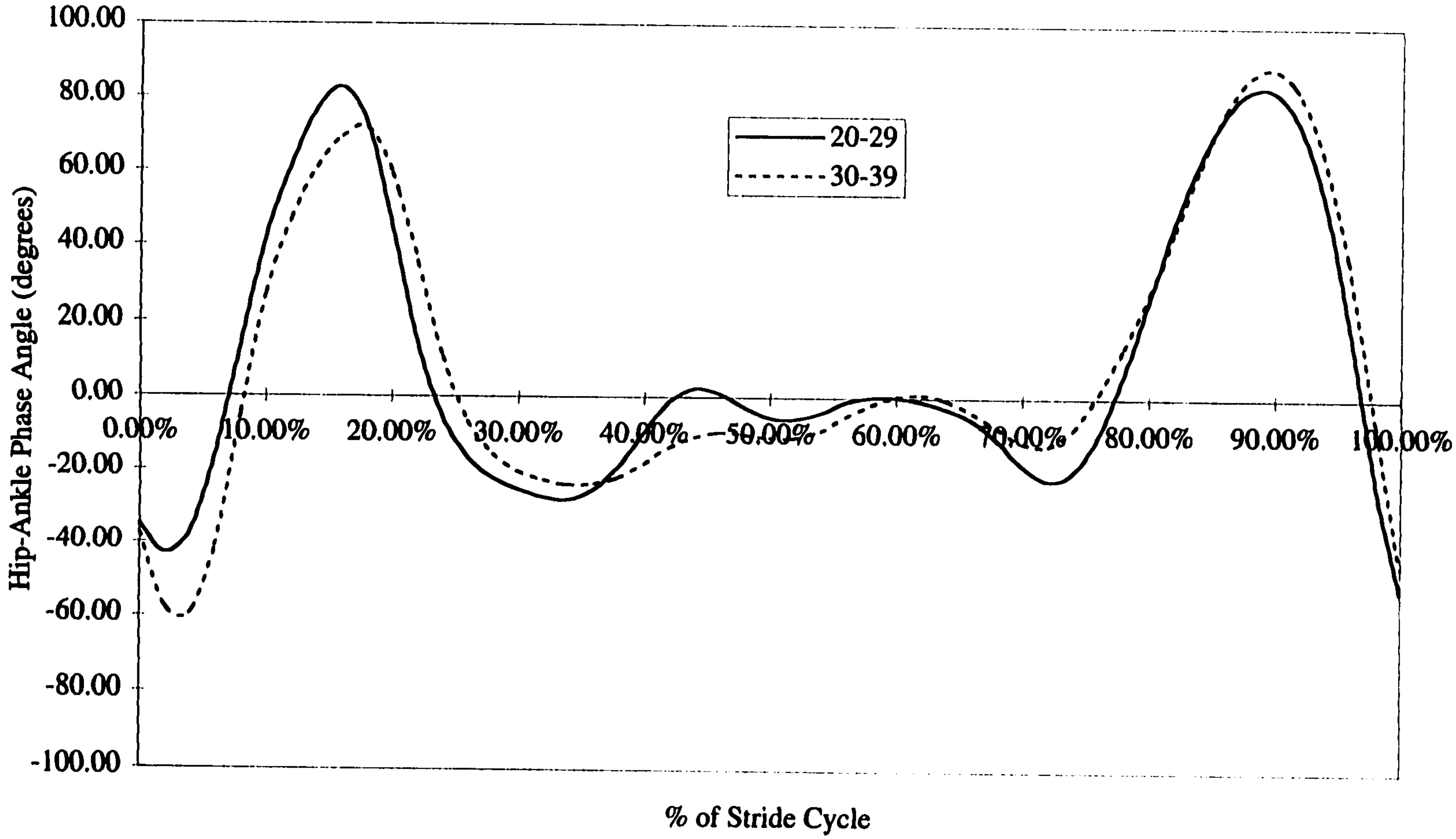


Figure 21. Normal Running Trial Comparison of the 20-29 Age Group vs. the 30-39 Age Group for the Hip-Ankle Phase Angle

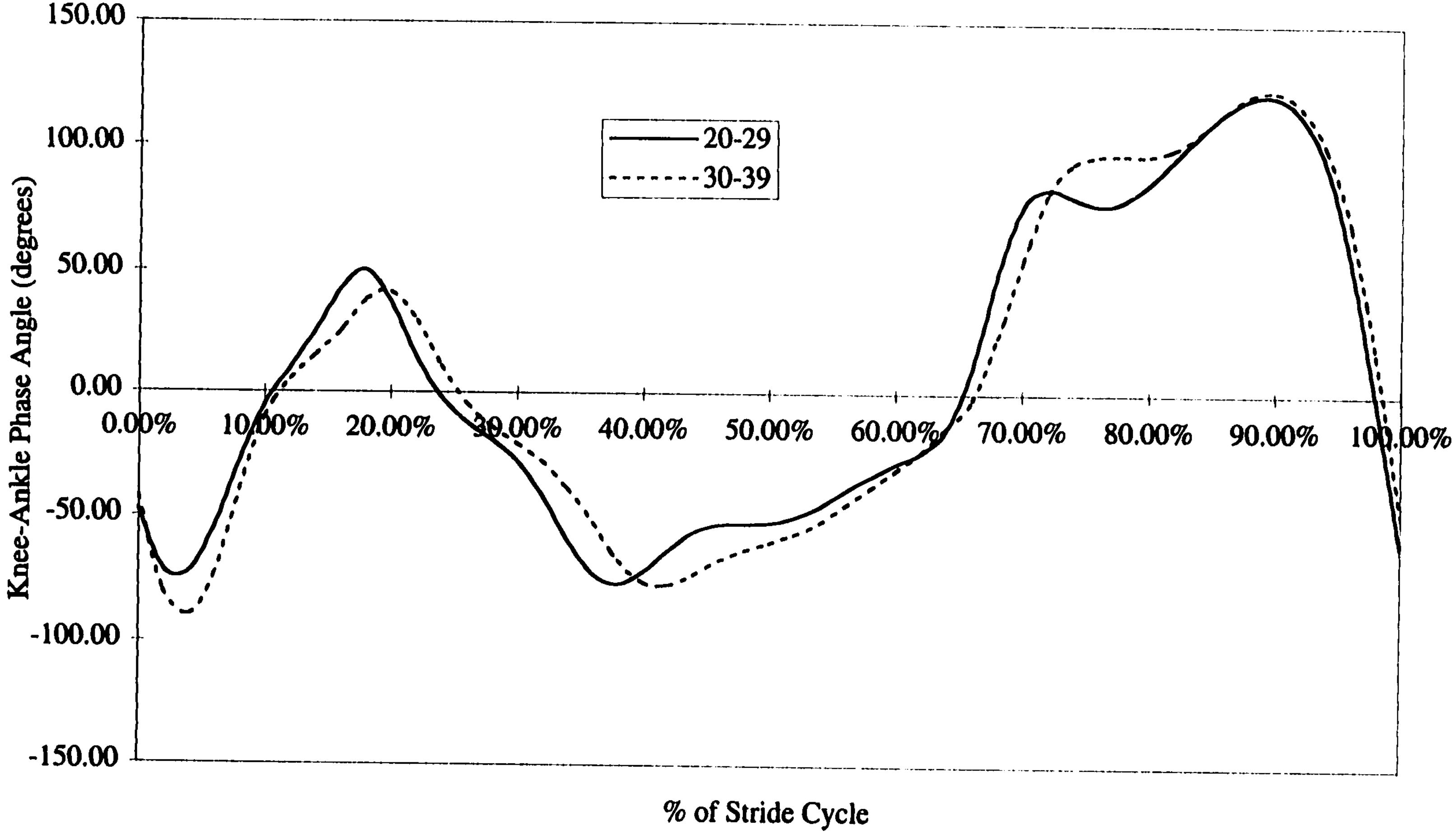


Figure 22. Normal Running Trial Comparison of the 20-29 Age Group vs. the 30-39 Age Group for the Knee-Ankle Phase Angle

of the normal running trials for the 20-29 age group and the 30-39 age group. Inspection of this figure also reveals a similar overall pattern for each age group.

Peak Ankle Angular Velocity

Mean values for peak ankle angular velocity during each locomotion trial are presented in Table 2. Results from a 2 (age) x 2 (gender) x 8 (trial) factorial ANOVA indicated a significant main effect for locomotion trial, $F(7,252) = 181.21$, $p < .001$. All other effects were not statistically significant ($p > .05$). The results of a Newman-Keuls post hoc comparison indicated peak ankle angular velocity during each locomotion trial was significantly different from peak ankle angular velocity during every other locomotion trial except for the two normal walking trials.

Summary

The following findings have been made based on the results of the data analysis. First, the attractor state of each collective variable being investigated does not qualitatively change as the speed of walking is increased. Second, the attractor state of each collective variable being investigated does not qualitatively change as the speed of running is increased. Third, the attractor state of each collective variable being investigated is qualitatively different for walking and running. Fourth, the attractor state of each collective variable being investigated is not qualitatively different when the walking trials of the 20-29 year old adults are compared to the walking trials of the 30-39 year old adults. Fifth, the attractor state of each collective variable being investigated is not qualitatively different when the running trials of the 20-29 year old adults are compared to the running trials of the 30-39 year old adults. Finally, the mean values for horizontal velocity and peak ankle angular velocity during the slow running trials were significantly greater than the mean values for horizontal velocity and peak ankle angular velocity during the fast walking trials.

Table 2

Mean Values for Peak Ankle Angular Velocity (deg/s)

	N Walking 1	S Walking	N Walking 2	F Walking	N Running 1	S Running	N Running 2	F Running
20-29 (male)	280.73	238.61	289.31	318.45	515.18	378.54	500.47	571.37
20-29 (female)	283.10	214.85	282.10	313.98	519.49	426.71	473.66	540.73
30-39 (male)	276.10	258.00	305.58	321.84	499.96	407.41	508.12	574.13
30-39 (female)	320.43	282.43	295.06	328.22	538.46	431.70	489.64	576.94

CHAPTER 5

DISCUSSION

In this chapter, the results of the study are discussed with respect to theoretical propositions of dynamic systems theory, to previous developmental research on aging and gait, and to previous kinematic research on the transition from walking to running. In the first section, whether the collective variables investigated in this study satisfy the theoretical selection criteria developed by Kelso and Schöner (1988) is discussed. Specifically, the results of this study are evaluated with respect to the first three hypotheses presented in chapter one. In the second section, the collective variables are evaluated with respect to previous developmental research on stability in locomotion associated with changes in age. Specifically, the results of this study are evaluated with respect to the fourth and fifth hypotheses presented in chapter one. A discussion on the differences in peak ankle angular velocity between the trials of fast walking and slow running is presented in the third section. Specifically, the results of this study are evaluated with respect to the sixth hypothesis presented in chapter one. The fourth section presents recommendations for future research. In the final section, a summary of the important conclusions and recommendations that can be drawn from the results of this study is presented.

Identifying a Collective Variable of Locomotion: Theoretical Requirements

The two criteria for identifying a collective variable of locomotion come from the propositions of dynamic systems theory (Kelso & Schöner, 1988). First, there must be a qualitatively stable attractor state of the collective variable for each phase of the movement behavior being investigated. In other words, as the value of a control parameter is varied during any phase of the movement behavior being investigated, the attractor state of the collective variable during that phase will remain qualitatively stable. In the case of locomotion, the objective is to identify a collective variable whose attractor states during walking and running remain qualitatively stable as the speed of locomotion is increased.

This theoretical requirement is addressed by hypotheses one and two. Specifically, a confirmation of these hypotheses indicates this theoretical requirement is satisfied.

The first hypothesis is no qualitative differences in the overall pattern of the attractor states of each collective variable will be evident when the four walking trials are compared. Presented on Figure 3 (page 46) are the attractor states of the hip-ankle relative phase angle for the four walking trials. The attractor states of the knee-ankle relative phase angle for the four walking trials are displayed on Figure 4 (page 47). For both collective variables, the overall pattern of the attractor state remained stable for increasing speeds of locomotion. The results presented on Figures 5 through 8 (pages 48-51) indicate that subject gender had no effect on the attractor states of walking in either age group. Based on the results presented on Figures 3 through 8, hypothesis one is confirmed.

The second hypothesis is no qualitative differences in the overall pattern of the attractor states of each collective variable will be evident when the fourn running trials are compared. Displayed on Figure 9 (page 52) are the attractor states of the hip-ankle relative phase angle for the four running trials. The attractor states of the knee-ankle relative phase angle for the four running trials are presented on Figure 10 (page 53). For both collective variables, the overall pattern of the attractor state remained stable for increasing speeds of locomotion. The results presented on Figures 11 through 14 (pages 54-57) indicate that subject gender had no effect on the attractor states for running in either age group. Based on the results presented on Figures 9 through 14, hypothesis two is confirmed. Confirmation of hypotheses one and two leads to a conclusion that both collective variables meet the first theoretical requirement for identifying a collective variable of locomotion.

The second theoretical requirement is the existence of a discontinuous phase shift from one attractor state of the collective variable to another attractor state of the collective variable as the value of a control parameter is varied (Kelso & Schöner, 1988). In the case of locomotion, the goal is to find a collective variable whose attractor state during walking discontinuously shifts to another attractor state during running as the speed of locomotion is increased. This theoretical requirement is addressed by hypothesis three. Specifically, refuting hypothesis three indicates this theoretical requirement is satisfied.

The third hypothesis is no qualitative differences in the overall pattern of the attractor states of each collective variable will be evident when the walking and running trials are compared. Presented on Figure 15 (page 59) are the attractor states of the hip-ankle relative phase angle for the two normal walking trials and the two normal running trials. From this figure, two qualitatively different attractor states are seen: one for walking and one for running. However, whether a discontinuous phase shift occurs or whether the change is continuous is not apparent from this figure. An inspection of Figure 16 (page 60) reveals that the same qualitative difference is apparent when the attractor state for fast walking and the attractor state for slow running are compared. If the shift from walking to running was continuous, the attractor states of fast walking and slow running would have come closer together. Instead, each attractor state retained the stable configuration of the specific type of locomotion (e.g., walking or running). Thus, a conclusion can be drawn that a discontinuous phase shift appeared to occur for the attractor state of this collective variable as the speed of locomotion was increased. Similarly, when the results presented on Figures 17 and 18 (pages 61-62) are examined, a conclusion can be drawn that a discontinuous phase shift appeared to occur for the attractor state of the knee-ankle relative phase angle as the speed of locomotion was increased. Thus, hypothesis three is refuted for both collective variables, and each collective variable satisfies the second theoretical requirement for identifying a collective variable of locomotion.

Identifying a Collective Variable of Locomotion: Developmental Requirements

From an adult developmental perspective, a collective variable must meet one criterion for identifying a collective variable of locomotion. It must identify similarities when similarities are expected between two age groups. In the case of adult locomotion, the objective is to find a collective variable whose attractor state during walking remains qualitatively stable when two age groups of young adults are compared. In addition, the attractor state for running should remain qualitatively stable when the same two age groups of young adults are compared. This developmental requirement is addressed by hypotheses four and five. Specifically, a confirmation of these hypotheses indicates this developmental requirement is satisfied.

The fourth hypothesis is no qualitative differences in the overall pattern of the attractor states of each collective variable will be evident when the walking trials of the 20-29 year-old age group and the 30-39 year-old age group are compared. The attractor states of the hip-ankle relative phase angle for the normal walking trials of the 20-29 year-old age group and the 30-39 year-old age group are presented on Figure 19 (page 63). Displayed on Figure 20 (page 64) are the attractor states of the knee-ankle relative phase angle for the normal walking trials of the 20-29 year-old age group and the 30-39 year-old age group. For both collective variables, the overall pattern of the attractor state remained stable when the two age groups were compared. Based on these results, hypothesis four is confirmed.

The fifth hypothesis is no qualitative differences in the overall pattern of the attractor states of each collective variable will be evident when the running trials of the 20-29 year-old age group and the 30-39 year-old age group are compared. Presented on Figure 21 (page 65) are the attractor states of the hip-ankle relative phase angle for the normal running trials of the 20-29 year-old age group and the 30-39 year-old age group. The attractor states of the knee-ankle relative phase angle for the normal running trials of the 20-29 year-old age group and the 30-39 year-old age group are displayed on Figure 22 (page 66). For both collective variables, the overall pattern of the attractor state remained stable when the two age groups were compared. Based on these results, hypothesis five is confirmed. Confirmation of hypotheses four and five leads to a conclusion that both collective variables meet the adult developmental requirement for identifying a collective variable of locomotion.

Peak Ankle Angular Velocity during Fast Walking and Slow Running

Hreljac (1995a) concluded that peak ankle angular velocity was the only kinematic variable that determined the transition from fast walking to slow running. In this study, peak ankle angular velocity decreased significantly at the transition from walking to running. This experimental finding is addressed by hypothesis six.

The results of a 2 (age) x 2 (gender) x 8 (trial) factorial ANOVA performed on the data presented in Table 2 (page 68) indicated that peak ankle angular velocity during the slow running trials was significantly greater than peak ankle angular velocity during the fast walking trials. Thus, the results of this study contradict the finding of Hreljac (1995a). Two possibilities exist that might explain this result. First, the mean horizontal velocity during the slow running trials (2.47 m/s) was significantly faster than the mean horizontal velocity during the fast walking trials (2.08 m/s). Hreljac (1995a) studied differences in peak ankle angular velocity when the speeds of fast walking and slow running were identical. Thus, the discrepancy between the finding of Hreljac (1995a) and the finding in this study could have been the result of the significant difference in horizontal velocity between the fast walking trials and the slow running trials. To further explore this possibility, linear trendlines were plotted for the peak values of ankle angular velocity during the four walking and four running trials. These plots are presented on Figure 23. An examination of this figure leads to the conclusion that linear extrapolation of the running data to a horizontal velocity equivalent to the mean of the fast walking trials still results in peak ankle angular velocity of running being faster than the peak ankle angular velocity of walking.

The second possible explanation for the discrepancy between the finding of Hreljac (1995a) and the finding in this study is differences in experimental methodology. Hreljac

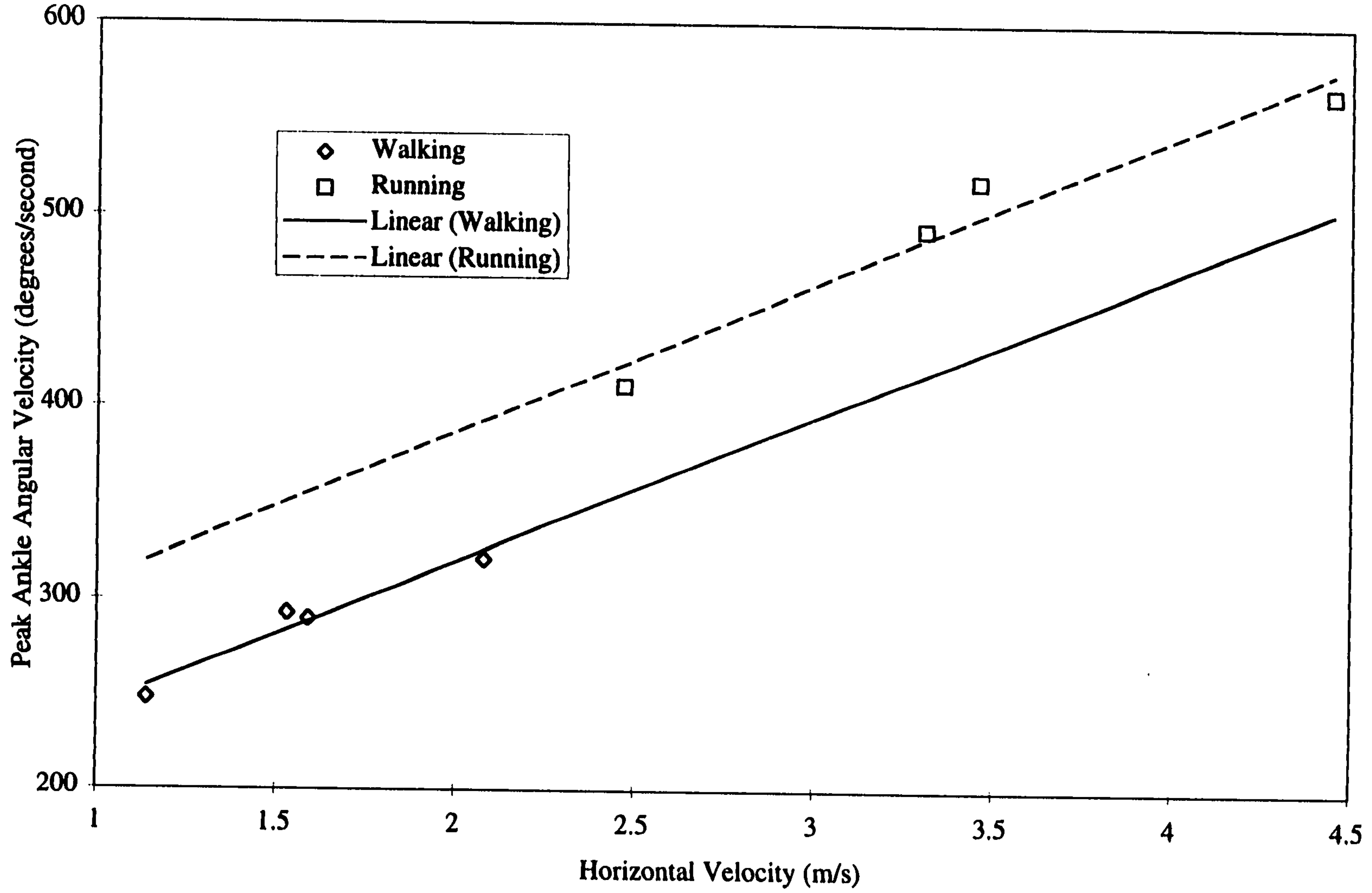


Figure 23. Trend Lines for Peak Ankle Angular Velocity

(1995a) specifically studied kinematic changes at the transition from walking to running. The experimental trials were performed on a motor driven treadmill. A preferred speed of transition from walking to running was determined for each subject. Then, each subject walked for 30 seconds at 70%, 80%, 90% and 100% of their preferred transition speed. Only one running trial was conducted. Each subject ran for 30 seconds at their preferred transition speed. In this study, the subjects performed self-selected walking trials for approximately 25 feet across a hardwood floor. The duration of each trial varied from approximately one-half second to two seconds. The transition from walking to running was not specifically investigated.

Future Research

A dynamic systems analysis of coordinated movement requires the identification of a collective variable which completely captures the essential characteristics of the movement pattern, the investigation of the collective variable's behavior (i.e., its attractor state) near a point of transition from one stable, movement pattern to a different stable, movement pattern, the identification of potential control parameters which drive the transition, and the investigation of the stability and loss of stability of the attractor state as the value of the control parameter is varied (Kelso & Schöner, 1988). In this study, two collective variables have been identified which satisfy the first three requirements. Future research should examine the stability and loss of stability of the attractor state for each collective variable as the speed of locomotion is varied.

Such an investigation might first identify the preferred speed of transition for each subject. Then, using a variable speed treadmill, each subject would perform a continuous experimental trial which incrementally increases the speed of locomotion from 50% of the preferred transition speed to 150% of the preferred transition speed. For each incremental increase in locomotion speed, the subject would walk or run until a steady state is achieved; then, the speed would be increased again. For each steady-state condition, the attractor state of the collective variable would be plotted for several consecutive strides. Stability and loss of stability would be evaluated as the amount of qualitative variation and quantitative variation (i.e., changes in standard deviation) of the attractor state during the four consecutive strides. Dynamic systems theory predicts the amount of variation in the attractor state would increase as the speed of walking approached the preferred transition speed. The subject would then switch to running. With further increases in the speed of running, the amount of variation in the attractor state would decrease.

Once it is determined that either or both of the collective variables tested in this study satisfies the last theoretical requirement of dynamic systems theory, a second developmental study should be conducted. In this study, the collective variables should be evaluated on their ability to identify developmental differences when developmental differences are expected. An appropriate experimental context would be the investigation of changes in walking patterns as children move from infancy into childhood.

From approximately the twelfth month of life to the seventh year of life, children progress from an immature to a mature form of walking (Payne & Issacs, 1995). Immature walking is characterized by the toes pointed outward, a wide base of support, short and quick steps, a flat-footed contact pattern, and the arms held high. Mature walking is characterized by the toes pointed in a forward direction, a narrow base of support, long and rhythmical steps, a heel-strike to toe-off contact pattern, and arms swinging in opposition to the legs. Thus, qualitatively different forms of walking exist at the beginning and end of this six-year period. A study investigating the development of walking for two age groups of young children (1-2 years and 7-8 years) could be used to verify that each collective variable of locomotion can identify developmental differences when developmental differences are expected.

To reduce intertrial variability, several methodological modifications should be considered. These include three-dimensional analyses, automatic digitizing, use of a treadmill, and having subjects wear tight-fitting shorts. During the walking and running trials, an observable amount of out-of-plane motion occurred. Since this motion varied in amount from subject to subject, and from trial to trial, intertrial variability increased. Three-dimensional analyses would accommodate these out-of-plane movements. During the data digitizing process, an observable amount of variability was noted when the experimenter manually located and digitized the joint markers. This variability was the result of three factors: experimenter hand-eye coordination, hand steadiness, and fatigue. An automatic digitizing system would eliminate these factors. Additional intertrial variability entered the analysis because of the short duration of each locomotion trial (one-half to two seconds). A steady state of locomotion was not attained. Use of a motor driven treadmill would allow subjects to perform each trial over a longer testing period. This would increase the likelihood of attaining a steady state of locomotion. Finally, subjects should be required to wear tight fitting shorts during the locomotion trials. An observable amount of extraneous movement was noted for the hip marker during the faster locomotion trials. This extraneous movement added to intertrial variability. The use of tight fitting shorts would eliminate this extraneous movement.

These suggested methodological modifications would reduce intertrial variability. However, the collective variables of locomotion investigated in this study did meet all theoretical and developmental identification criteria. Thus, these suggested modifications to reduce intertrial variability would serve to strengthen the positive findings of this study.

Conclusions and Recommendations

The attractor states of the collective variables evaluated in this study qualitatively distinguished two different, stable states of locomotion. The attractor states also demonstrated an abrupt phase transition from one stable attractor state to another stable attractor state as the value of a control parameter was increased. In addition, the collective variables demonstrated qualitatively similar attractor states for walking and for running when two age groups of young adults were compared.

Recommendations for future research include testing of an additional theoretical prediction and comparing the locomotion patterns of infant walkers and young children. The additional theoretical prediction would specifically study the phase transition from walking to running from both qualitative and a quantitative perspectives. The developmental comparison would investigate the qualitative differences in the attractor states of each collective variable of locomotion when developmental differences are expected. Several methodological changes should be considered when future studies are conducted. These include conducting three-dimensional analyses, using a motor-driven treadmill and automatic digitizing of the videotape data.

Summary

Two collective variables of locomotion were tested against two theoretical and two developmental selection criteria. Both collective variables satisfied the four selection criteria. Therefore, continued investigation of these collective variables is warranted. First, the stability and loss of stability of the attractor state of each collective variable should be investigated as the speed of locomotion is varied. Second, each collective variable's ability to identify developmental differences when developmental differences are expected should be tested. Several methodological modifications should be considered when future studies of collective variables of locomotion are performed. These include three-dimensional analyses, automatic digitizing, and use of a treadmill. The results of this study support an overall conclusion that the hip-ankle relative phase angle and the knee-ankle relative phase angle are theoretically and developmentally viable collective variables of locomotion.

REFERENCES

Baldissera, F., Cavallari, P., & Civaschi, P. (1982). Preferential coupling between voluntary movements of ipsilateral limbs. Neuroscience Letters, 34, 95-100.

Bernstein, N. (1967). The co-ordination and regulation of movements. Oxford: Pergamon Press.

Blanke, D. J., & Hageman, P. A. (1989). Comparison of gait of young men and elderly men. Physical Therapy, 69, 144-148.

Centers for Disease Control and Prevention. (1993). Health data on older Americans: United States, 1992. (National Center for Health Statistics, Vital and Health Statistics, Series 3: Analytic and Epidemiological Studies, No. 27).

Clark, J. E., & Phillips, S. J. (1993). A longitudinal study of intralimb coordination in the first year of independent walking: A dynamical systems analysis. Child Development, 64, 1143-1157.

Clark, J. E., Truly, T. L., & Phillips, S. J. (1990). A dynamical systems approach to understanding the development of lower limb coordination in locomotion. In H. Bloch & B. I. Bertenthal (Eds.), Sensory-motor organizations and development in infancy and early childhood (pp. 363-378). Dordrecht: Kluwer.

Clark, J. E., Whitall, J., & Phillips, S. J. (1988). Human interlimb coordination: The first 6 months of independent walking. Developmental Psychobiology, 21, 445-456.

Craik, R. (1990). Changes in locomotion in the aging adult. In M. H. Woollacott & A. Shumway-Cook (Eds.), Development of posture and gait across the life span (pp. 177-201). Columbia, South Carolina: University of South Carolina Press.

Haken, H., Kelso, J. A. S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. Biological Cybernetics, 51, 347-356.

Hreljac, A. (1993a). Determinants of the gait transition speed during human locomotion: Kinetic factors. Gait and Posture, 1, 217-223.

Hreljac, A. (1993b). Preferred and energetically optimal gait transition speeds in human locomotion. Medicine and Science in Sports and Exercise, 25, 1158-1162.

Hreljac, A. (1995a). Determinants of the gait transition speed during human locomotion: Kinematic factors. Journal of Biomechanics, 28, 669-677.

Hreljac, A. (1995b). Effects of physical characteristics on the gait transition speed during human locomotion. Human Movement Science, 14, 205-216.

Kelso, J. A. S. (1981). On the oscillatory basis of movement. Bulletin of the Psychonomic Society, 18, 63.

Kelso, J. A. S. (1984). Phase transitions and critical behavior in human bimanual coordination. American Journal of Physiology, 240, R1000-1004.

Kelso, J. A. S., Holt, K. G., Kugler, P. N., & Turvey, M. T. (1980). On the concept of coordinative structures as dissipative structures. II. Empirical lines of convergence. In G. E. Stelmach & J. Requin (Eds.), Tutorials in motor behavior (pp. 49-70). New York: North Holland.

Kelso, J. A. S., Holt, K. G., Rubin, P., & Kugler, P. N. (1981). Patterns of human interlimb coordination emerge from the properties of non-linear, limit cycle oscillatory processes: Theory and data. Journal of Motor Behavior, 13, 226-261.

Kelso, J. A. S., & Scholz, J. P. (1985). Cooperative phenomena in biological motion. In H. Haken (Ed.), Complex systems - operational approaches in neurobiology, physical systems and computers (pp. 124-149). Berlin: Springer.

Kelso, J. A. S., Scholz, J. P., & Schöner, G. (1986). Nonequilibrium phase transitions in coordinated biological motion: Critical fluctuations. Physics Letters A, 118, 279-284.

Kelso, J. A. S., & Schöner, G. (1987). Toward a physical (synergetic) theory of biological coordination. In R. Graham & A. Wunderlin (Eds.), Lasers and synergetics: A colloquium on coherence and self-organization in nature (pp. 224-237). Berlin: Springer-Verlag.

Kelso, J. A. S., & Schöner, G. (1988). Self-organization of coordinative movement patterns. Human Movement Science, 7, 27-46.

Kelso, J. A. S., Schöner, G, Scholz, J. P., & Haken, H. (1987). Phase-locked modes, phase transitions and component oscillators in biological motion. Physica Scripta, 35, 79-87.

Kelso, J. A. S., & Tuller, B. (1984). A dynamical basis for action systems. In M. Gazzaniga (Ed.), Handbook of cognitive neuroscience (pp. 321-356). New York: Plenum Press.

Kugler, P. N., Kelso, J. A. S., & Turvey, M. T. (1980). On the concept of coordinative structures as dissipative structures. I. Theoretical lines of convergence. In G. E. Stelmach & J. Requin (Eds.), Tutorials in motor behavior (pp. 3-47). New York: North Holland.

Kugler, P. N., Kelso, J. A. S., & Turvey, M. T. (1982). On the control and coordination of naturally developing systems. In J. A. S. Kelso & J. E. Clark (Eds.), The development of movement control and coordination (pp. 5-78). New York: Wiley.

Leiper, C. I., & Craik, R. L. (1991). Relationships between physical activity and temporal-distance characteristics of walking in elder women. Physical Therapy, 71, 791-803.

National Center for Health Statistics, Vital Health Statistics. (1993). Health promotion and disease prevention: United States, 1990.

Òunpuu, S. (1994). The biomechanics of walking and running. Clinics in Sports Medicine, 13, 843-863.

Payne, V. G., & Isaacs, L. D. (1995). Human motor development: A lifespan approach (3rd ed.). Mountain View, CA: Mayfield Publishing Company.

Scholz, J. P., Kelso, J. A. S., & Schöner, G. (1987). Nonequilibrium phase transitions in coordinated biological motion: Critical slowing down and switching time. Physics Letters A, 123, 390-394.

Schöner, G., Haken, H., & Kelso, J. A. S. (1986). A stochastic theory of phase transitions in human hand movement. Biological Cybernetics, 53, 247-257.

Schöner, G., & Kelso, J. A. S. (1988). Dynamic pattern generation in behavioral and neural systems. Science, 239, 1513-1520.

Thelen, E. (1986). Treadmill-elicited stepping in seven-month-old infants. Child Development, 57, 1498-1506.

Thelen, E. (1989). Self-organization in developmental processes: Can systems approaches work? In M. R. Gunnar & E. Thelen (Eds.), Systems and development: The Minnesota symposia on child psychology (pp.77-117). Hillsdale, New Jersey: Lawrence Erlbaum.

Thelen, E., & Ulrich, B. D. (1991). Hidden Skills: A Dynamic systems analysis of treadmill stepping during the first year. Monographs of the Society for Research in Child Development, 56 (1, Serial No. 223).

Thelen, E., Ulrich, B. D., & Niles, D. (1987). Bilateral coordination in human infants: Stepping on a split-belt treadmill. Journal of Experimental Psychology: Human Perception and Performance, 13, 405-410.

Thomas, J. R., & Nelson, J. K. (1990). Research methods in physical activity (2nd ed.). Champaign, IL: Human Kinetics Books.

U.S. Bureau of the Census (1990). The need for personal assistance with everyday activities: Recipients and caregivers (Current Population Reports, Series P-70, No. 19). Washington, DC: U.S. Government Printing Office.

U.S. Department of Health and Human Services. (1991). Aging America: Trends and Projections (DHHS Publication No. (FCoA) 91-28001).

Whitall, J., & Getchell, N. (1995). From walking to running: Applying a dynamical systems approach to the development of locomotor skills. Child Development, 66, 1541-1553.

Yamanishi, J., Kawato, M., & Suzuki, R. (1980). Two coupled oscillators as a model for the coordinated finger tapping by both hands. Biological Cybernetics, 37, 219-225.

Appendices

Appendix A
Health Screening Questionnaire

Health Screening Questionnaire

Subject ID#: ______________________________

Age: ______________________________

Height (cm): ______________________________

Weight (N): ______________________________

Gender (Male/Female): ______________________________

Any known nervous system disorder(s) that affect(s) your ability to walk or run?

____

____

____

Any known medical condition(s) that affect(s) your ability to walk or run?

____

____

____

Any known muscle, joint, or bone disorders that affect(s) your ability to walk or run?

____

____

____

Please state the average number of days per week you exercise, the average amount of time you exercise on those days, and the average level of intensity (low, moderate, or high).

____

____

____

Appendix B
Informed Consent to Participate in Research

SJSU SAN JOSE STATE UNIVERSITY

A campus of The California State University

College of Applied Sciences and Arts • *Department of Human Performance*
One Washington Square • San José, California 95192-0054 • 408/924-3010 • FAX 408/924-3053

Informed Consent to Participate in Research

I am being invited to participate in research that will investigate the transition from walking to running. The results of this study will further our understanding of the development of walking and running and may assist us identifying and rehabilitating individuals who are experiencing problems with their walking patterns.

I understand that:

1) I will be asked to complete a health screening questionnaire. The questionnaire will ask four questions concerning my current state of health and physical fitness. In addition, information about my age, height, weight, and gender will be requested. Age, gender and health status are the subject selection criteria for this study.

2) If selected, I will be asked to wear a dark-colored t-shirt, dark-color shorts, and walking/running shoes during the testing. I will have tape markers placed on several joints of my body. I will be asked to perform four walking trials (one at a slow walking pace, two at a normal walking pace, and one at a fast walking pace) and four running trials (one at a slow runing pace, two at a normal running pace, and one at a fast running pace). I will be videotaped during each walking or running trial. The entire procedure will take about 45 minutes.

3) The possible risks to me from this study are minimal. However, though highly unlikely, minor injuries (such as muscles strains or pulls) can occur with any movement activity.

4) I may benefit from this study by learning about the proper biomechanics of walking and running.

5) The results of this study may be published, but any information from this study that can be identified with me will remain confidential and will be disclosed only with my permission.

6) I will not receive any compensation for participation in this study.

7) Any questions concerning the research will be answered by Jim Kao at (415) 594-3220. Complaints about the procedures may be presented to Dr. Greg Payne at (408) 924-3028. For questions or complaints about my rights, or in the event of research-related injury, contact Dr. Serena Stanford (Associate Academic Vice President for Graduate Studies & Research) at (408) 924-2480.

8) My consent is given voluntarily without any coercion. I may refuse to participate in this study, and I may withdraw my consent at any time without prejudice to the my relations with San Jose State University.

9) I will receive a copy of this consent form for my files.

HAVING READ THE INFORMATION PROVIDED ABOVE, I HAVE MADE A DECISION WHETHER OR NOT TO PARTICIPATE IN THIS STUDY. MY SIGNATURE BELOW INDICATES THAT I AM WILLING TO PARTICIPATE.

DATE

PARTICIPANT'S SIGNATURE

INVESTIGATOR'S SIGNATURE

Appendix C
Description of the Testing Procedure

Description of the Testing Procedure

"The order of the trials will be normal walking, slow walking, normal walking, fast walking, normal running, slow running, normal running, and fast running. For the slow walking trials, you will be asked to walk as slowly as you can without stopping. For a normal walking trial, you will be asked to walk at your preferred or normal speed of walking. For the fast walking trial, you will be asked to walk as fast as possible without running. For the slow running trial, you will be asked to run at a slow jogging pace. For a normal running trial, you will be asked to run at your preferred or normal speed of running. For the fast running trial, you will be asked to run at a speed faster than your normal speed of running."